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An Annotated Bibliography of Thermal Radiation Validation Data for Fire Applications

John R. Howell, Kyle Daun, and Hakan Erturk

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An Annotated Bibliography of Thermal Radiation Validation Data for Fire Applications*

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Abstract

This report details experimental data useful in validating radiative transfer codes involving participating media, particularly for cases involving combustion. Special emphasis is on data for pool fires.

Features sought in the references are: Flame geometry and fuel that approximate conditions for a pool fire or a well-defined flame geometry and characteristics that can be completely modeled; detailed information that could be used as code input data, including species concentration and temperature profiles and associated absorption coefficients, soot morphology and concentration profiles, associated scattering coefficients and phase functions, specification of system geometry, and system boundary conditions; detailed information that could be compared against code output predictions, including measured boundary radiative energy flux distributions (preferably spectral) and/or boundary temperature distributions; and a careful experimental error analysis so that code predictions could be rationally compared with experimental measurements.

Reference data were gathered from more than 35 persons known to be active in the field of radiative transfer and combustion, particularly in experimental work. A literature search was carried out using key words. Additionally, the reference lists in papers/reports were pursued for additional leads.

The report presents extended abstracts of the cited references, with comments on available and missing data for code validation, and comments on reported error. A graphic for quick reference is added to each abstract that indicates the completeness of data and how well the data mimics a large-scale pool fire. The references are organized into Lab-Scale Pool Fires, Large-Scale Pool Fires, Momentum-Driven Diffusion Flames, and Enclosure Fires. As an additional aid to report users, the Tables in Appendix A show the types of data included in each reference. The organization of the tables follows that used for the abstracts.

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INTRODUCTION

This report details the results of a search for experimental data that can be used to validate radiative transfer codes involving participating media, particularly for cases involving combustion. Special emphasis is on data for pool fires.

To be useful for code validation, the following features were sought:

1. Flame geometry and fuel that approximate conditions for a pool fire or, lacking that, a well-defined flame geometry and characteristics that can be completely modeled.
2. Detailed information that could be used as code input data. This should include species concentration and temperature profiles and associated absorption coefficients, soot morphology and concentration profiles, associated scattering coefficients and phase functions, specification of system geometry, and system boundary conditions.
3. Detailed information that could be compared against code output predictions. This information would include measured boundary radiative energy flux distributions (preferably spectral) and/or boundary temperature distributions.
4. A careful experimental error analysis so that code predictions using input data from 2.) could be rationally compared with experimental measurements of 3.).

Reference data were gathered from two primary sources. First, over 35 persons known to be active in the field of radiative transfer and combustion, particularly in experimental work, were contacted with a request for references or reports that meet the above criteria and/or leads to others who might provide such data. Second, a literature search was carried out using key words, and additionally the reference lists in papers/reports were pursued for additional leads.

Coupling between the fluid mechanics and the heat transfer, particularly in pool fires, presents a challenge to both numerical analysts and experimentalists. It is a challenge for experimentalists to simultaneously measure local velocities, species and soot

concentrations, and temperatures. It is unlikely that a complete input data set can be obtained for a radiative transfer code that requires solution of an energy equation that incorporates chemical energy generation, soot generation and morphology, advection, conduction and radiative transfer. In addition, it is necessary to measure or compute all of the necessary properties required in the governing equations. If only the radiative transfer equation is to be solved for a given temperature profile and given radiative properties, then the situation is considerably better, because the radiative transfer solution is then considered independent of the fluid mechanics. However, even in this case, the local species and soot concentrations must be known in order to calculate or estimate the necessary radiative properties.

The material presented in this report consists chiefly of extended abstracts of the cited references, with comments on available and missing data for code validation, and comments on reported error. Comments are added on the suitability of each reference for Sandia's use in validation.

A graphic for quick reference is added to each abstract, with the vertical scale indicating the completeness of data available for code input and data on radiative output for comparison. The horizontal axis indicates how well the data mimics a large-scale pool fire. These scales should be recognized as being quite qualitative, and that they reflect the judgment of the authors of this report as to how well the material in the papers meets the requirements for code validation. They are not a reflection of the quality of work reported in the references, but only how well the material reported in the reference meets the criteria for validation of the SIERRA/FUEGO or SIERRA/SYRINX code.

The references are organized into four sections: Lab-Scale Pool Fires, Large-Scale Pool Fires, Momentum-Driven Diffusion Flames, and Enclosure Fires. Pool fires are all taken to be buoyancy-driven, and are categorized by whether they experiments were conducted indoors and were immune to wind effects (Lab-Scale) or outdoors (Large-Scale). The lab-scale fires tend to be more easily studied in the experiments. Momentum-Driven Diffusion Flames are even more easily controlled, characterized and studied experimentally. For this reason, they provide excellent test cases for predictive code verification even though they do not simulate the more chaotic conditions typical of pool

fiores. Enclosure fires are difficult to model and to experimentally quantify, and most of the references do not include complete data for modeling purposes. However, some references may have value and have been included. Clearly, this is not a perfect categorization, but it serves the purposes of this report. Within each section, the abstracts are ordered alphabetically.

As an additional aid to report users, the Tables in Appendix A show the types of data included in each reference. The organization of the tables follows that used for the abstracts..

The authors of this report consider the following references to be the most useful for code validation:

Lab-Scale Pool Fires:

Fischer et al. (1987)

Zhang et al. (1993 and Zhang et al. (1991)

Large-Scale Pool Fires:

Kramer et al. (2001)

Momentum-Driven Diffusion Flames:

Faeth et al. (1989)

Faeth et al. (1988)

Gore et al. (1987)

You and Faeth (1982)

Each of these references has complete input data sets as well as measurements of radiative flux. Except in one case, they have good experimental error analyses.

LAB-SCALE POOL FIRES

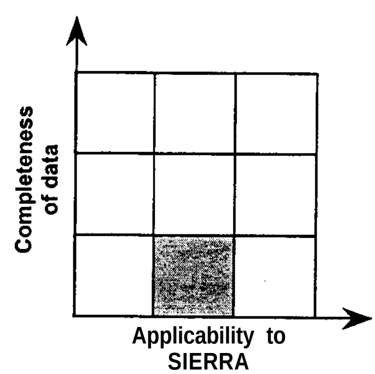
Bouhafid, A., Vantelon, J. P., Joulain, P., and Fernandez-Pello, A. C., 1988, "On the Flame Structure at the Base of a Pool Fire," Proc. 22nd Symposium (International) on Combustion, The Combustion Institute, pp. 1291-1298.

This paper presents the species concentration, temperature, and monochromatic absorption coefficient in the base region of a moderately sized kerosene pool fire. The experimental apparatus consists of a 15 cm diameter, 3 cm deep fire pan. The pan is filled with kerosene to a depth of 2 mm (1 mm below the pan lip) and this fuel level is maintained throughout the experiment. The flame is confined in a test cell that is vented by natural convection, in order to minimize the effects of ambient drafts.

Temperature measurements are obtained using a thermocouple array. The temperature measurements are time averaged, and the variations in the mean are less than 5%. It is not clear if the thermocouple measurements have been corrected for radiation effects. Composition measurements are made by first extracting samples from the fire, passing them through infrared analyzers that measure CO and CO_2 concentrations, and to a gas chromatograph that measures O_2 concentrations. The CO and CO_2 measurements are averaged, and the variation is less than 3%. The O_2 measurements have an uncertainty of 6%. The absorption coefficient is measured by laser attenuation, at 633 nm. These measurements have uncertainties of up to 30%.

All measurements are taken in the base region of the fire, called the "persistent zone" because it is characterized by a luminous flame with constant shape and structure. Data include a contours plot of the temperature distribution, species concentration, and absorption coefficient at 633 nm in this region. (The latter is used to predict soot concentrations.)

This paper will be of limited use for the present study. The accuracy of the temperature data is questionable, however, (experimental uncertainly is based solely on a statistical analysis of the data, and does not account for systematic error), and velocity and radiant flux measurements were not included. Nevertheless, the temperature and species concentration measurements are detailed, and may be used to validate the chemistry module of the SIERRA/FUEGO or SIERRA/SYRINX code.

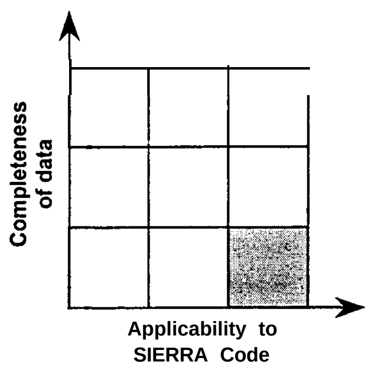


Burgess, D., and Hertzberg, M., 1974, "Radiation from Pool Flames," from Heat Transfer in Flames, N.H. Afgan and J.M. Beer, Eds., Scripta Book Co., Washington D. C., Ch. 27, pp. 413-430.

This reference contains a considerable amount of data concerning the properties of pool fires and diffusion flames collected from different published works. The main purpose of the study is to assess the risk posed by radiation emitted from a pool fire resulting from an accidental spill. Diffusion flames burning hydrogen, methane, butane, and ethylene, and pool fires burning methanol, LNG, butane, gasoline, and benzene were studied.

A significant amount of the data concerns the burning rate of the pool, which is used to estimate the total thermal output per unit liquid surface. The flame temperature of a heptane pool fire is plotted as a function of air/fuel weight ratio. Radiation data consists of plots of radiance measurements and absorption coefficients as a function of wavelength, although the experimental apparatus, measurement technique, and measurement location are unspecified. The radiative fraction for different gaseous and liquid-supported diffusion flames is also presented in tabular form.

This paper is of limited use to the present study. Very little information is provided concerning the experimental apparatus, and no uncertainty analysis is provided. (This information may be available in the original publications, however.) Also, all of the data is macroscopic in nature; no differential information (such as velocity or temperature profiles) is provided. If this source can be used, it would be to validate the overall performance of the SIERRA/FUEGO or SIERRA/SYRINX code, rather than an individual module.



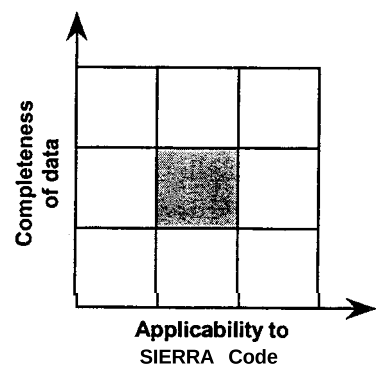
Choi, M. Y., Hamins, A., Rushmeier, H., and Kashiwagi, T., 1994, "Simultaneous Optical Measurement of Soot Volume Fraction, Temperature, and CO_2 in Heptane Pool Fire," *Proc. 25th Symposium (International) on Combustion,* The Combustion Institute, pp. 1471-1480.

The goal of the study is to determine the relative importance of the radiation component in the heat feedback to the fuel surface, compared to the other modes of heat transfer. In the experiments, the temperature, soot fraction, and CO_2 concentration were measured for a 10 cm-diameter heptane pool fire. This data was then used to determine the H_2O and CO species concentrations from generalized state relationships, and the radiant flux incident on the pool surface was calculated using a reverse Monte-Carlo technique.

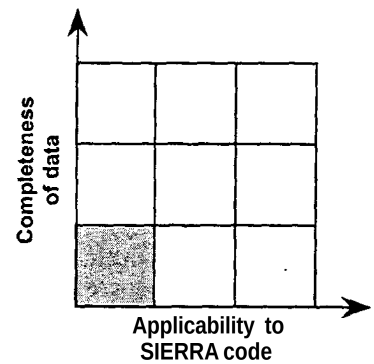
The temperature and soot volume fractions were carried out optically, by measuring emissive power. The temperature and soot volume fraction measurements had an estimated error of 50 K and 10%, respectively. The CO_2 was measured using a PbSe detection system. These data were then supplied to the RADCAL inverse Monte-Carlo program, which solved for the radiant flux incident on the fuel surface. The error in the radiant heat flux is estimated to be 1 W/m^2, which is less than 10% of the measured value.

Results presented include the Monte Carlo results for the radial distribution of radiant heat flux incident on the pool surface and plots showing the time average distributions of temperature, soot volume fraction, CO_2, H_2O and CO at one axial location.

The usefulness of this paper is limited because most of the data is presented in a form that would make comparison to numerical results difficult. Also, the radiation fluxes are not measured directly, but are instead found numerically based on other data. Thus, the accuracy of this data is very doubtful. Nevertheless, heat flux incident on the fuel surface is of particular interest to the study, so this paper may prove somewhat useful for validating the radiation module of the SIERRA/SYRINX code.



Crauford, N. L., Liew, S. K., and Moss, J. B., 1985, "Experimental and Numerical Simulation of a Buoyant Fire," ***Combustion and Flame,*** **Vol.** ***61*****, pp. 63-77.**



This paper presents the velocity and temperature fields from a buoyant, turbulent natural gas fire. The experimental apparatus consists of a 25 cm diameter circular porous refractory burner, fueled by natural gas (>95% methane). This apparatus is surrounded by solid walls on three sides, and a fine wire mesh on the fourth side to limit the effects of ambient drafts. Combustion air is entrained from the laboratory through the mesh screen.

Temperature is measured using a thermocouple array and the velocity measurements are made with a laser Doppler anemometer. The experimental uncertainties of these measurements are not provided.

Data include temperature, probability density functions of temperature, and the axial velocity component, both measured at the centerline and plotted as a function of height and measured at one axial station and plotted as a function of radial location.

This paper is of limited use for the present study, since no radiation measurements are taken, and the experimental uncertainties are unknown. Also, the complicated burner geometry may hamper numerical modeling. Nevertheless, the velocity and temperature measurements in the fire may be useful for validating the fluid mechanics module of the SIERRA/FUEGO or SIERRA/SYRINX code.

Fischer, S., Hardouin-Duparc, B., and Grosshandler, W., 1987, "The Structure and Radiation of an Ethanol Pool Fire," *Combustion and Flame,* Vol. 70, pp. 291-306.

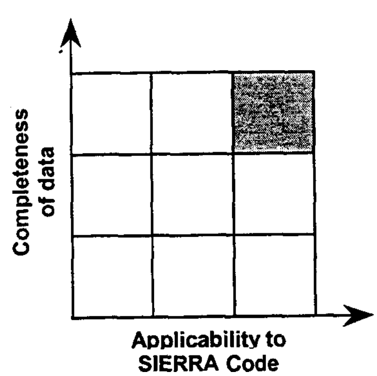
This paper provides a very detailed description of the flame above a 0.5 m diameter ethanol pool fire. Data include the concentration of the combustion products, the temperature distribution, and the velocity distribution from the pool surface to a height of 1.5 m. The local soot absorption coefficient and radiant intensity distributions are also measured.

The species concentration in the combustion products is measured using a commercial NDIR process analyzer for the CO and CO_2 concentrations, and a gas chromatograph for the hydrocarbon concentrations. The experimental error in this process is estimated to be 15%. The gas temperature is measured with a thermocouple array; this data is adjusted to account for thermal lag and radiation loss. The soot extinction coefficient is measured using an argon laser, and the total radiation heat flux is determined using both wide- and narrow- angle radiometers.

The composition of the combustion products is evaluated at 21 different radial positions and 3 different heights above the fire. Temperature data include contour plots at two heights above the fire, the average radial temperature profiles at eight heights above the fire, and vertical temperature profiles evaluated at six radial positions. The error in the temperature measurements based on the standard deviation of the data, is approximately 325 K, or about 25% at worst. The thermocouple probe is also used to estimate the velocity profile using a cross-correlation technique. The radial velocity profiles at three different heights are provided.

Radiation data consist of the centerline total radiant intensity evaluated at fifteen different heights, and the intensity parallel to the surface of the pool, evaluated at ten radial locations. Based on the error bars on the graphs, the error in the radiation intensity appears to be approximately 25%. This paper also compares the radiant intensity distributions obtained experimental to two numerical simulations.

This reference will prove to be extremely valuable to the present application. The reported data can be used to validate almost every aspect of the fire code. Both the velocity and temperature fields are described in detail, and the radiation emitted from the fire is well documented.

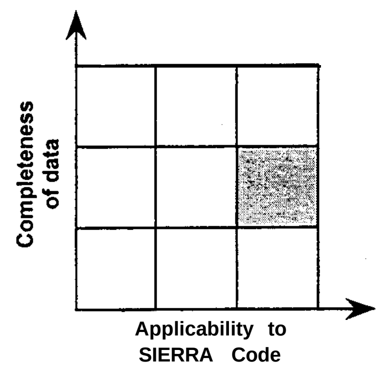


Hamins, A., Klassen, M. E., Gore, J. P., Fischer, S. J., and Kashiwagi, T., 1994, "Heat Feedback to the Fuel Surface of Pool Fires," *Combustion Science and Technology,* Vol. 97, pp. 37-62.

This paper presents measurements designed to investigate the heat feedback to pool fires burning liquid fuels. The experimental apparatus is an annular-ring pool burner with a 0.3 m diameter. The radial variation of the total radiant heat fluxes incident on the pool are measured at various angles, using a narrow-view radiometer. Other Data include average flame height, average mass burning rate, heat release fraction, heat loss rates from this experiment and several published sources. Fuels include heptane, toluene, methyl alcohol, and methyl methacrylate.

The paper discusses the flame character for the different fuels, and compares many different data to other published experiments and correlations. The principle results presented concern the heat feedback rates and the incident radiant heat flux distribution over the pool surface. Radiative measurements include the intensity and heat flux incident on the pool surface, measured at 10 radial locations, and the reflectivity of the pool surface, as a function of polar angle. The intensity measurements are taken in eight directions at each radial station. Mass burning rates, mass flux rates, and heat feedback rates at each radial location are also included.

This paper prove very useful for validating the radiation module of the SIERRA/SYRINX code, since the radiation emitted by the fire is well characterized. The radiant heat feedback to the fire is of particular interest, since



it can be used to approximate the heat flux incident on a low-profile object immersed in a pool fire, which is the scenario of direct interest to this study. Unfortunately, this paper lacks an adequate estimate of error, largely because the apparatus is unique. (Repetition of the tests indicate an uncertainty of approximately 10%, for the wide angle total heat flux gauge.) Also, the paper does not include any velocity or temperature measurements in the fire.

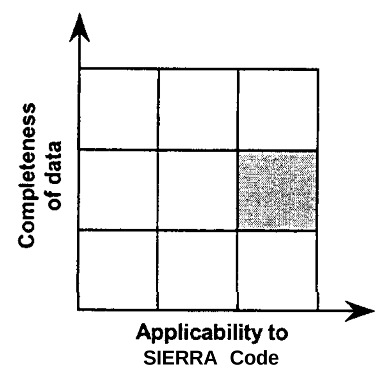
Hamins, A., Klassen, M., Gore, J., and Kashiwagi, T., 1991, "Estimate of Flame Radiance via a Single Location Measurement in Liquid Pool Fires," *Combustion and Flame,* Vol. 86, pp. 223-228.

The goal of this paper is to develop a correlation to estimate the heat loss (radiative) fraction using a radiance measurement at a single location. The heat loss fraction estimates determined from a single measurement are compared to those calculated using radiant data obtained at multiple locations around the fire.

Pools with diameters of 4.6, 7.1, and 30 cm were studied. The fuels studied were heptane, toluene, styrene, methyl methacrylate, methanol, ethanol, hexanol, and a homogeneous azeotropic mixture of 70% toluene and 30% ethanol by volume. The fuel level was maintained 4 mm below the rim of the burner for the duration of the test. The distribution of radiant energy to the surroundings was determined by moving a wide-angle radiometer over a "semi-infinite" cylindrical surface surrounding the fire.

Reported data include the flame height, a plot of the radiant heat flux from a 30-cm diameter heptane flame as a function of height above the pool surface, and plots of the heat-loss fraction for pools burning heptane, methanol, and ethanol, for all pool diameters. Tabulated data include the heat-loss fraction for all fuel types and pool diameters. A comprehensive error analysis is presented, which suggests that the standard deviation in repeated heat flux measurements at the same location ranges from 10% to 20%.

This paper shall be particularly useful for validating the radiation module of the SIERRA/SYRINX code. A wide range of pool diameters and fuel types were studied, and the quality of the data appears to be quite high. It would be more useful, however, to obtain the local radiation heat flux measurements used to calculate the heat-loss fraction.



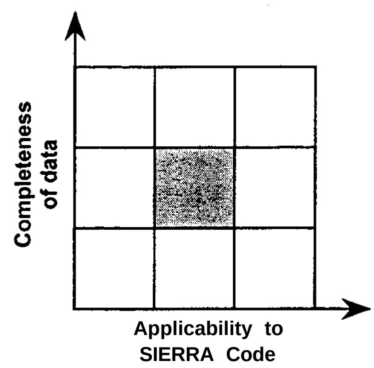
Hogben, C. D. A., Young, C. N., Weckman, E. J., and Strong, A. B., 1999, "Radiative Properties of Acetone Pool Fires," ***Proc. 1999 National Heat Transfer Conference,*** **Albuquerque, NM, August.**

This paper discusses the link between the flame geometry and the radiant output of the fire. This is done by first measuring the radiation distribution at various locations to determine the spatial variation of the radiation, using narrow-angle and wide-angle radiometers. Both sets of results were then used independently with the geometric characteristics of the fire to approximate the total radiant heat output. Finally, the radiation distribution is used to evaluate a new in-field technique that uses video and thermocouple data to estimate heat flux and radiative fraction of the fire.

The experimental apparatus consisted of a 3 1 cm diameter acetone pool fire. The entire apparatus was contained within a screened enclosure to minimize the effects of ambient drafts. Three different thermopile radiometers (two wide-angle, one narrow-angle) were positioned at a height of 31 cm above the pool surface and pointed at the central axis of the pool. The wide-angle detectors and narrow angle detectors were positioned 1.5 and 3 m away from the fire, respectively. The fire was also videotaped, and the resulting image was digitally altered to define eight color regions corresponding to different flame temperatures.

Results presented include the flame height, the emissive power, radiative fraction, and flame temperature. These data are calculated using the narrow-angle and wide-angle radiometer data and the thermocouple/video data, and are in good agreement with each other and with other published data (typically within 1 0%.)

This paper does not reprot the temperature and velocity fields within the tire, which limits its usefulness to the present study. Nevertheless, the radiation data is of a high quality so this paper should prove to be moderately useful for validating the radiation module of the SIERRA/SYRINX code.



Inamura, T., Saito, K., and Tagavi, K. A., 1992, "A Study of Boilover in Liquid Pool Fires Supported on Water. Part II: Effects of In-depth Radiation Absorption," ***Combustion Science and Technology,*** **Vol. 86, pp. 105-119.**

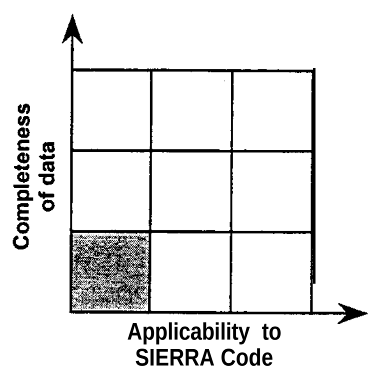
This paper presents a one-dimensional model that predicts the time required for a sub-layer of water to begin boiling. The model requires radiation absorption, which is experimentally determined. The total radiant heat flux at the fuel surface was measured for a toluene and *n*-decane pool fire, and the effective average absorption coefficient was measured for toluene and Alberta Sweet crude oil. The total heat flux measurements were carried out on a stainless steel pan with a 12 cm diameter and a 2 cm height. A fine wire mesh surrounded the pool fire to minimize the effects of ambient drafts.

The radiant heat flux was measured using a Gardon-gauge type radiometer inserted through a l-cm diameter pipe passing though the center of the pool. The radiometer was aligned with the fuel surface, and measured the radiant feedback to the pool surface from the fire.

The absorption coefficient was measured on a pool fire based in a Pyrex pan with a diameter of 12 cm, and a height of 2 cm. The pan was filled with fuel and ignited. After 10 s, the radiant heat passed from the fire through the fuel layer was measured with a Gardon-gage type radiometer located under the fuel surface, and aimed at the bottom surface of the Pyrex pan.

Data for this experiment includes the radiant heat feedback at the time of boilover, plots of total heat flux passed through the fuel layer as a function of fuel layer thickness, fuel surface velocity as a function of fuel layer thickness, the boilover temperature as a function of initial fuel temperature, and the boilover time as a function of boilover temperature and fuel layer thickness.

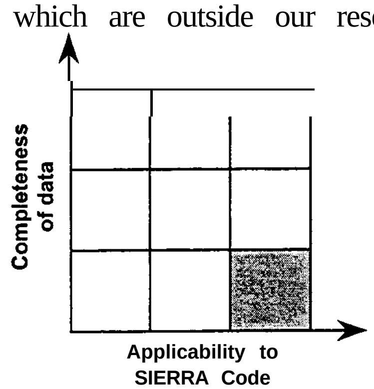
This paper is of limited use to the study. Boilover is not relevant to the present study and very little auxiliary data is provided. Also, no formal error analysis is included. Nevertheless, the radiative feedback measurements are relevant to the accident scenario of interest for validating the radiation module of the SIERRA/SYRINX code, as this data may be used to estimate the radiation heat transfer from a flame to a low-profile object immersed in a pool fire.



Joulain, P., 1996, "Convective and Radiative Transport in Pool and Wall Fires: 20 Years of Research in Poitiers," *Fire Safety Journal,* Vol. *26*, pp. 99-149

This paper summarizes research carried out by University of Poitiers, France, in the last two decades that is focused on convective and radiative transfer in combustion systems. The studies are classified in five main topics. These are gas-solid combustion in horizontal configuration, gas-solid combustion in a vertical configuration, bottom surface combustion and soot radiation, tire and gravity and research in progress. Rather than presenting details of experiments and their result, brief conclusions are drawn referencing the corresponding journal or conference paper.

Gas-solid combustion in the horizontal configuration resembles the horizontal turbulent wall fire and in the experiments carried out, it was observed that radiation is not significant and negligible at laboratory scales. The gas-solid combustion in a vertical configuration resembles the vertical wall fires and convection is the predominant mode of heat transfer, especially for high confinement. Radiation becomes important as the scale of the burner rises. The research on bottom surface combustion and soot radiation consists of gathering mass fraction, concentration and property data to provide necessary information for an accurate radiation calculation. Pool or natural fire research involves theoretical and experimental investigation of simulated pool fires and liquid pool fires. Souil et al. (1984) is one of the referenced studies that provides comparisons of experimental and theoretical heat flux values of a pool fire. The details of the study are presented in the review of the relevant paper. The liquid fire research focuses on the study of the radiative transfer between free-burning fires and their surroundings. The research investigating the effects of an externally applied thermal radiant heat flux on a kerosene pool fire is presented in Zhang et al. (1991), which includes measurements of temperature and concentration and how they are effected by the external radiation applied. Zhang et al. (1993) further investigates the influences over the radiative flux from the flame on the environment. More detailed information about these articles is presented individually. Other studies summarized regarding the pool fires include the case where the flame is tilted as in flames resulting in most of the real accidents due to wind conditions. The next main topic of study is gravity effects, which are outside our research interest.



The paper references many articles, conference papers and technical reports; therefore this could be good source of information to keep in the database.

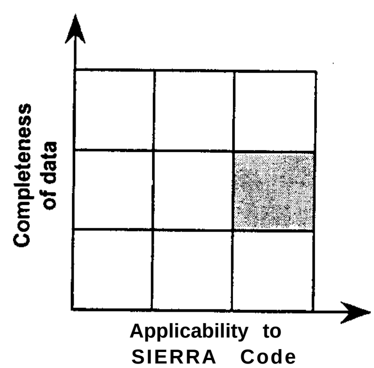
Klassen, M., Gore, J. P., and Sivathanu, Y. R., 1992, "Radiative Heat Feedback in a Toluene Pool Fire," *Proc. 24th Symposium (International) on Combustion,* The Combustion Institute, pp. 1713-1719.

This paper gives measurements of the radiative heat flux incident on the fuel surface of a toluene pool fire, and the soot volume fractions based on emission and absorption. This data is then used to develop a treatment for the equation of radiative transfer that accounts for turbulent fluctuations of the heat feedback.

The experimental apparatus consists of a 30 cm diameter toluene pool fire. The radiative intensity is measured using a narrow- angle radiometer positioned 2 mm above the liquid surface on a pivot, in order to obtain measurements in different directions. The soot volume fractions are measured with a laser.

Results include the radial distributions of the mean and RMS temperature and soot volume fractions based on emission and absorption, evaluated at three different heights above the pool surface. Radiative data include the radial distribution of intensity incident on the liquid surface evaluated in three different directions, and the radial distribution of the total hemispherical heat flux. No error analysis is provided.

This paper will be very useful for validating the radiation module of the SIERRA/SYRINX code. The radiation data is in an accessible format, and the experimental apparatus is described in a detailed way so numerical modeling should be quite easy. The radiative feedback measurements are of particular interest since they can be used to estimate the radiant flux incident on a low-profile object immersed in the pool fire, which is one of the accident scenarios to be considered in this study. Unfortunately, the lack of an uncertainty analysis and supporting data (temperature and velocity measurements) somewhat limits the usefulness of this data.



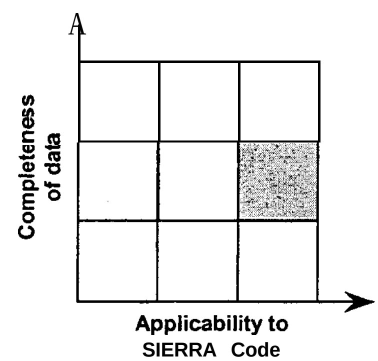
Koseki, H., 1994, "Boilover and Crude Oil Fire," *Journal of Applied Fire Science,* Vol. 3, no. 3, pp.243-271

This article describes the boilover phenomena in detail and presents a brief summary of the literature about the topic. The author uses various experimental results that were conducted at FRI (Fire Research Institute), NIST (National Institute of Standards and Technology) while explaining the details of the phenomena. The setups used in these experiments consist of a pan filled with water and fuel floating on top. Circular pans with diameters of 0.3 m, 0.6 m, 1.0 m, and 2.0 m, as well as a 2.7 m x 2.7 m square pan are considered. The measurements are carried out for Arabian and Louisiana crude oil, kerosene, and fuel oil.

A number of thermocouples are placed at certain heights along the fire axis and along the two other radial locations. The fuel is ignited and the incident thermal radiation from the flame is measured using a radiometer located at various distances to the pan axis.

Besides the incident thermal radiation, the distributions of temperature are also presented along with the burning time. The input provided for the experiments are the pan diameter, fuel thickness, average and maximum fuel regression rate, and heat wave regression rate. The uncertainty for the measurements is estimated to be 5%.

Although the boilover phenomenon is not of interest to the present study, the radiation and temperature data could prove to be useful for validating the radiation module of the SIERRA/SYRINX code, particularly in the case of sooty flames.



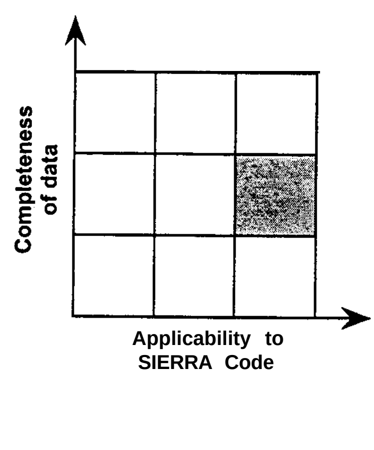
Koseki, H., and Yumoto, T., 1988b, "Air Entrainment and Thermal Radiation from Heptane Pool Fires," ***Fire Technology,*** **Vol. 24, pp. 33-47.**

This paper describes air entrainment into heptane pool fires, and characterizes the smoke-blocking effect on thermal radiation from the fire. Pool fires with diameters of 0.3 m, 0.6 m, 1 m, 2 m, and 6 m were studied. In each case, about 3 cm of fuel floated on a pool of water. Once the fuel was ignited, it was not replenished. The burning rate was determined by measuring. the liquid surface regression rates. The 0.3, 0.6, and 1 m fires were conducted in a 15 m × 30 m × 18 m enclosed test facility, while the 2 m and 6 m fires were conducted outdoors.

Temperature was measured using an array of sheathed K-type thermocouples located throughout the fire. The 2 m and 6 m pool fires had arrays of 64 and 58 thermocouples respectively, while the remaining experiments were instrumented with 80 thermocouples. Gas velocity measurements were calculated using pressure measurements from an array of nine bi-directional stainless steel pressure probes, assuming a gas density equal to the density of air at the measured temperature. Total radiation from the flame was measured using five wide-angle (120°) thermopile detector radiometers. The radiometers were installed at various radial distances away from the fire, level with the pan lip and aligned with the tire axis. Radiation from horizontal slices of the flame was measured using five narrow-angle radiometers, each with a different viewing angle.

Plots are given of burning rate as a function of tank diameter, time-averaged velocity along the flame axis as a function of height, and mean velocity as a function of pan diameter. Further plots show temperature profiles along the flame axis for all pan diameters, and a contour plot of temperature over the entire fire domain for the 6 m pool fire. Radiation measurements include radiant heat flux as a function of distance from the fire, radiation heat flux as a function of pan diameter, and radiant emittance as a function of height. The mass air entrainment is also calculated by assuming a "top-hat" velocity profile and that the flame is cylindrical with its diameter equal to the pan diameter.

This paper may be useful for code validation. The temperature and velocity fields are well characterized, and radiation measurements are included. Also, the experiment closely matches the accident scenario of interest. No error analysis is included, and the accuracy of the velocity calculations is suspect. The orientation of the fuel surface to the pan lip strongly influences the tire properties, but is not well defined.



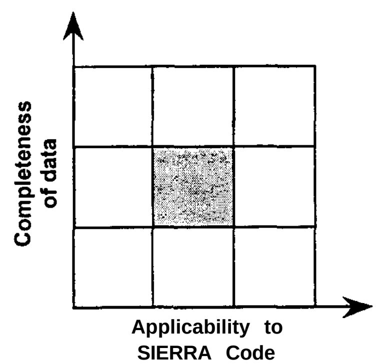
Markstein, G. H., 1981, "Scanning-Radiometer Measurements of the Radiance Distribution in PMMA Pool Fires," *Proc. 18th Symposium (International) on Combustion,* The Combustion Institute, pp. 537-547.

A scanning radiometer is used to produce a complete map of the averaged radiance of a 0.73 m diameter polymethyl methacrylate (PMMA) pool fire. Statistical properties of the radiation fluctuations are also presented. Finally, a simplified analytical model uses the radiance data to compute the axisymmetric distribution of a gray emission-absorption coefficient.

The experimental apparatus consists of a scanning radiometer located some distance away from the tire. The radiometer beam is directed using two magnetically actuated mirrors, allowing vertical and horizontal scanning of the complete flame region. The results are averaged over a large number of scans. No experimental uncertainty is provided.

Results presented include the radial profile of the averaged radiance evaluated at thirteen heights above the pool surface, and the variation of radiance with height above the pool surface, measured at seven different radial stations, the statistical data describing the fluctuation of the flame radiance due to turbulence, and the axisymmetric absorption coefficient distribution, calculated assuming a constant flame temperature.

The data presented in this paper will be somewhat useful for validating the radiation module of the SIERRA/SYRINX code since the radiation measurements are quite comprehensive. In particular, this data would be useful to validate the treatment of an optically thick (sooty) flame, which results from the combustion of PMMA. The usefulness of this paper is limited by the lack of an uncertainty analysis, and because no temperature or velocity measurements are included. . Furthermore, the accuracy of the absorption coefficient data is suspect because the calculations are done assuming a uniform flame temperature, which would seem to be an unreasonable assumption.



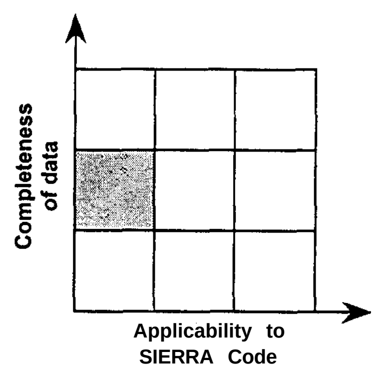
Modak, A. T., and Croce, P. A., 1977, "Plastic Pool Fires," *Combustion and Flame,* Vol. 30, pp. 251-265.

The purpose of this paper is to characterize the influence on radiation feedback on the burning behavior of 51-mm thick solid, horizontal, square, polymethyl methacrylate (PMMA) pool fires. Eleven pool sizes ranging from 25 mm x 25 mm to 1.22 m x 1.22 m were tested. Two tests were performed for all but two of the pool sizes. The PMMA slab was ignited by applying an accelerant mixture of PMMA chips, paraffin oil, and pentane uniformly over the slab surface.

The radiative power of the flame was calculated assuming isotropic flame radiation, and was based a single irradiance measurement taken with a wide-angle radiometer located three to four pool lengths from the pool center and at a height equal to one pool length. The radiometer was aimed at the fire axis. The fuel consumption rate was determined by continuously weighing the slab as it was burned. No uncertainty estimates are provided for any of this data.

Data include plots of burning rate and radiative fraction plotted against time after ignition and as a function of pool size, flame emissivity as a function of location, and burning rate due to radiant feedback as a function of location on the slab. Tabulated data include steady-state radiative fraction and radiative heat flux, steady state and time-averaged burning rate, time-dependant burning rates and heat flux

This paper should prove somewhat useful for the purposes of this study. Most of the data is provided in both graphical and tabular form. Unfortunately, no experimental uncertainty is included and the assumption of isotropic flame radiation is somewhat suspect. Also, the fuel is in solid form, which may complicate modeling. Also, velocity and temperature measurements are not included.



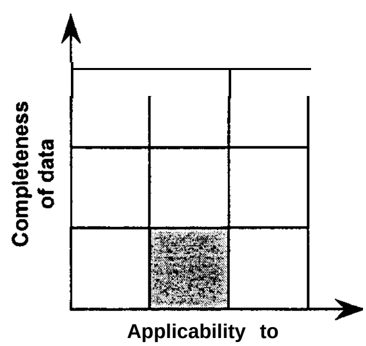
Orloff, L., 1981, "Simplified Modeling of Pool Fires," *Proc. 18th Symposium (International) on Combustion,* The Combustion Institute, pp. 549-561.

This paper develops a simplified model for predicting the radiant output of pool fires. A method is developed whereby a fire that has non-uniform temperature and species concentration can be represented by an equivalent fire with homogeneous properties. This model is tested against experimental measurements of polymethyl-methacrylate pool fires with diameters of 0.38 and 0.73 m. The fuel is in the form of solid plastic pellets. The pellets are placed on a moveable platform, which in turn rests on inner tubes. The inner tubes are inflated during the duration of the test to maintain a constant distance between the fuel surface and the burner lip. The entire apparatus is contained within a screened enclosure to minimize the effects of ambient drafts.

The flame shape was determined using a modified 35 mm camera, located seven diameters from the pool fire and aimed horizontally at the fire. The film images were digitized, and a statistical technique was employed to determine the *rms* flame radius at different heights above the pool surface. These results are compared to data from Markstein (1981), consisting of contours of constant radiance over the flame region obtained from averaged scanning radiometer measurements for the 0.73 m fire. The averaged absorption-emission coefficient and the average flame temperature as a function of height are presented. Also, the average flame temperature and absorption coefficient are plotted as a function height above the fuel surface.

The most useful data from this paper is the radiant flux measured at a target 2.8 m from the center of a 381 mm diameter PMMA pool fire, using a wide-angle radiometer. The results are plotted at various fuel heights within the burning pan. No error analysis is provided, although the analytical solutions lie within 12% to 15% of the experimental measurements.

This paper is moderately useful for code validation, although most of the experimental data reported comes from other published sources. Unfortunately, the lack of experimental uncertainty and supplemental data (radial temperature profiles and velocity measurements) limits the usefulness of this source. Also, the fuel is initially in solid form, which may complicate the numerical simulation.



Shinotake, A., Koda, S., and Akita, K., 1985, "An Experimental Study of Radiative Properties of Pool Fires of an Intermediate Scale," ***Combustion Science and Technology,*** **Vol. 43, pp. 85-97.**

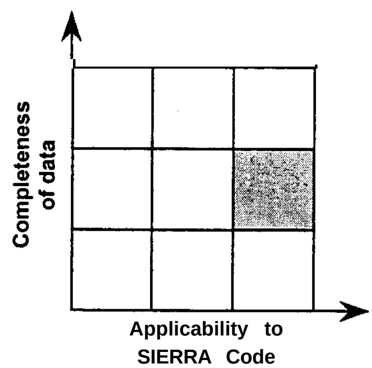
The goal of the paper is to investigate radiation heat transfer as a heat feedback mechanism for pool fires. In particular, the transient behavior of radiation heat flux incident on the pool surface at the time of ignition, and the ratio of internal to external radiation heat flux during steady burning are evaluated for several different pool diameters. Several different correlations are then developed and evaluated.

The apparatus consists of an iron pan partially filled with water. Heptane is floated on top of the water, and then ignited. Pool fires with diameters of 0.3 m, 0.7 m, and 1.0 m were studied.

The radiant heat flux values were measured inside and outside of the flame, using a Gardon-type radiometer and a wide-angle radiometer, respectively. The extinction coefficient of the flame soot is also measured with a chopped He-Ne laser beam. No experimental uncertainty is reported.

Data include the radiation heat flux incident on the center of the liquid surface plotted against time while the fire is burning, the ratio of internal and external radiative flux measurements, and the radiative heat flux distribution at different radial positions. The paper also presents the soot absorbance and volume fraction measured at three different heights, for three different pool diameters.

This reference will prove to be valuable in validating the radiation module of the SIERRA/SYRINX code. The radiation data is very comprehensive. Of particular interest are the radiation heat feedback measurements that can be used to estimate the heating of a low-profile object immersed in the pool; this is the accident scenario of primary interest to the present study. Unfortunately, no other supporting data (temperature and velocity distributions) are included, and experimental uncertainty is not provided.



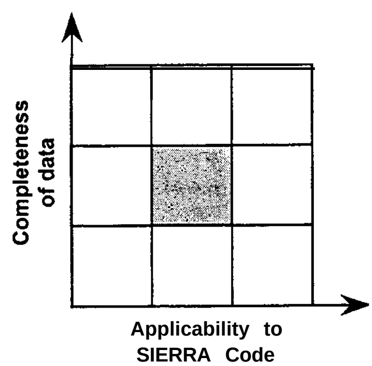
Sivathanu, Y.R. and Gore, J.P., 1992, "Transient Structure and Radiation Properties of Strongly Radiating Buoyant Flames," *Journal of Heat Transfer,* Vol. 114, pp. 659-665.

This paper describes the radiation emitted by buoyant-turbulent acetylene and propylene diffusion flames. The experimental apparatus consists of a 50 mm diameter burner tube, cooled by a water jacket. Little information is provided regarding the experimental apparatus, although another paper is referenced for further detail.

All measurements were done using a three-line absorption/emission probe. The intensity leaving the probe volume was collected divided into three parts by two beam-splitters. The intensities at 900 and 1000 nm were measured using calibrated photomultiplier tubes. The absoption coefficient was calculated based on the extinction of a 632.8 nm HeNe laser beam. These data were used to calculate the temperature and soot volume fraction.

The temperature, soot volume fraction and the intensity are measured at a single axial point and the radial profiles of mean and fluctuating temperatures and soot volume fractions for fires with different Reynolds numbers are presented. The uncertainties in absorption and emission soot volume fractions are reported to be 40% and 25%, respectively. The conditional probability density functions of temperature conditioned on absorption and emission soot volume fractions and the probability density functions of spectral radiation intensity are developed to display the statistical properties of the turbulent diffusion flame. The mean and rms spectral intensities for different flame conditions calculated from the temperature and soot volume fractions measured through correlations are compared with the measured intensities.

This paper is of little use for the present study, since measurements are taken only at one axial location, and the reported experimental uncertainty is quite large. Nevertheless, the spectral intensity and absorption data may prove useful to validate the radiation code.



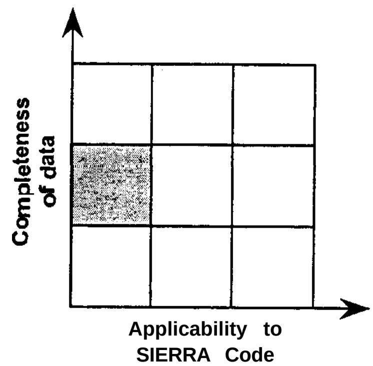
Weckman, E.J., and McEwen, C.S., 1991, "The Time Dependent Structure of a Medium-Scale Methanol Pool Fire," ***Proceedings of the ASME/JSME Joint Conference,*** **1991, Vol. 5, pp. 270-275.**

This paper describes the transient and time-averaged velocity and temperature profiles of a 305 mm methanol pool fire. The apparatus is contained within a screened enclosure in order to minimize the effects of ambient drafts.

The velocity field is calculated using LDA, and the temperature field is determined with a thermocouple array. Measurements of both velocity and temperature were taken at 20 mm intervals from the pool center to beyond the rim, and from heights of 20 to 200 mm above the pool surface, for a total of 121 stations. The *rms* velocity and temperature measurement errors were estimated to be 5% based on a statistical analysis of the data although there is some concern that systematic errors may be induced due to instrumentation errors and the thermal inertia of the thermocouple bead.

The centerline temperature measured at various heights above the pool surface is compared with published results from pool fires using different fuels (methane, acetone, ethane, ethyl alcohol, methyl alcohol, kerosene, and JP-4.) Significant variation is observed between the temperature profiles from the different fires.

This work does not contain any radiation data, so it cannot be used to validate the radiation module of the SIERRA/SYRINX code. Nevertheless, the temperature, velocity, and turbulence characteristics of the fire are well characterized, so this paper may be of some use in validating turbulence simulation in pool fires.

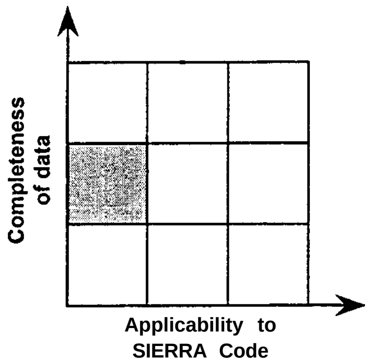


Weckman, E. J., and Strong, A. B, 1996, "Experimental Investigation of the Turbulence Structure of Medium-Scale Pool Fires," *Combustion and Flame*, Vol. 105, pp. 245-266.

The purpose of this paper is to describe the turbulent structure of a medium-scale methanol pool fire, which drives entrainment and mixing and therefore control development of the fire flow field. The experimental apparatus consists of a 3 l-cm diameter methanol pool fire, burning in quiescent conditions.

Laser Doppler anemometry was used to calculate the radial and axial components of velocity, while the temperature field was determined using thermocouples. Data include graphs of both mean and root mean squared temperature and velocity measured at 11 radial stations and 11 vertical stations (resulting in 12 1 measurements), and a variety of turbulence statistics including Reynolds stresses and turbulent heat flux terms. The velocity measurements are considered accurate to within 5%, at 95% confidence. The Reynolds stress measurements are accurate to within 15% at 95% confidence. The error in the temperature measurements is not available.

This paper will be particularly useful for the present application because of the large number of data points used to characterize the velocity and temperature flow fields. Also, this experiment should be easy to model, since the experiment is conducted under controlled conditions and the apparatus is described in detail. Also, the experimental uncertainty is well characterized and quite low. The turbulent properties of the fire are also well documented. Unfortunately, this paper does not include any radiation measurements.

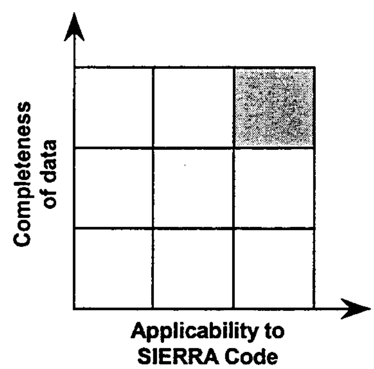


Zhang, X. L., Vantelon, J. P., and Joulain, P., "Thermal Radiation from a Small-Scale Pool Fire: Influence of Externally Applied Radiation," *Combustion and Flame*, Vol. 92, pp. 71-84.

This paper describes the effects of externally applied radiation on a small-scale kerosene pool fire. The experiments are performed with a small-scale kerosene pool fire, burning in a circular steel pan with a 15 cm diameter and depth of 5 cm. The external radiative fluxes are generated by radiant heating panels located in the ambient free stream, but far enough from the flame region to minimize the interference with flow induced by the fire. Four panels are positioned with respect to pool axis. Each panel consisted of four emitters, each delivering 400W nominal power. Four different imposed flux values are considered (80%, 90%, 100% of nominal value and 100% of nominal value located 10 cm below) together with the undisturbed case, where there is no external radiation imposed. The paper includes detailed information about the setup and measurement techniques used.

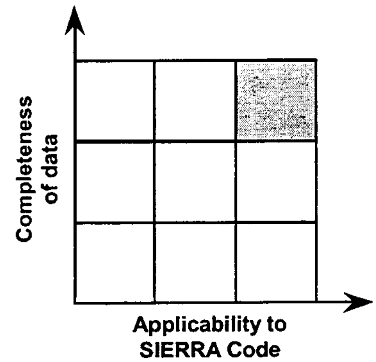
Temperature distributions, concentrations of CO_2, H_2O and CO, monochromatic absorption coefficient, soot absorption concentration, net radiative heat fluxes from the flame to the environment or to the fuel surface are all measured. The paper also includes a comparison between the radiative intensities along the axis calculated accounting for wavelength dependence and with the equivalent gray properties. A simple zonal analysis is employed to calculate the heat fluxes from the flame to the environment and to the fuel surface and compared with measurements.

This paper provides a complete set of the information necessary to solve the radiation equation for the flame together with its accompanying article Zhang et. al (199 1). The experiment is similar to the accident scenario likely to be encountered in the present study, except at a smaller scale and under controlled conditions. Because the radiation properties of the flame are described in detail, this paper will be particularly useful for validating the radiation module of the SIERRA/SYRINX code.



Zhang, X. L., Vantelon, J. P., Joulain, P. and Fernandez-Pello, A. C., 1991, "Influence of an External Radiant Flux on a 15-cm-Diameter Kerosene Pool Fire," *Combustion and Flame,* Vol. 86, pp. 237-248.

This article is the complementary article of Zhang et. al (1993) that includes the detailed information about the CO_2, H_2O and CO concentrations, absorption coefficient and temperature distributions. The article investigates the effects of external radiation on the maximum temperature in the flame region, burning rate of the fuel, flame shape and structure, temperature and concentration fields.



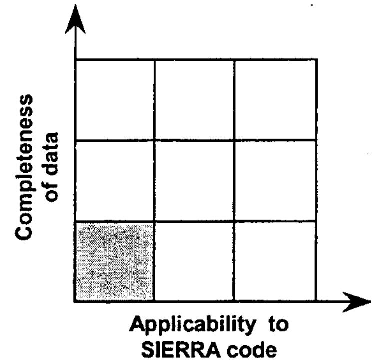
LARGE-SCALE POOL FIRES

Brosmer, M. A., and Tien, C. L., 1987, "Radiative Energy Blockage in Large Pool Fires," ***Combustion Science and Technology,*** **Vol. 51, pp. 21-*37.***

This paper discusses the influence of the fuel-rich core region of a pool tire of radiant heat transfer, and consequently the effect on burning behavior. A simplified model is proposed to account for this behavior, and is validated by comparing predicted results with experimental results obtained from PMMA pool fires. All the experimental data is taken from other published sources.

Data of interest includes plots of soot volume fraction as a function of non-dimensionalized height above the flame taken from five different pool fires, spectral absorption coefficients for the combustion gasses, radiant heat flux variation along the fuel surface as a function of radial distance, and radiative feedback as a function of pool size. Tabulated data include external radiative fraction, convective, surface re-radiant, and radiant heat flux (all calculated), as well as measured mass burn rate. No uncertainty estimates are provided for any of the experimental measurements, but these might be obtained from the references.

This paper will not be very useful for code validation. Although the reported experiments are similar to the scenario of interest, very little information about each experimental set-up is provided. Also, no temperature or velocity data is provided for any of the experiments. Nevertheless, the data may be of some use for validating the soot-chemistry model of the SIERRA/FUEGO or SIERRA/SYRINX code.



Fire and Blast Engineering Project, Fire and Blast Information Group (FABIG), UK Steel Construction Institute, Final Report, 1997.

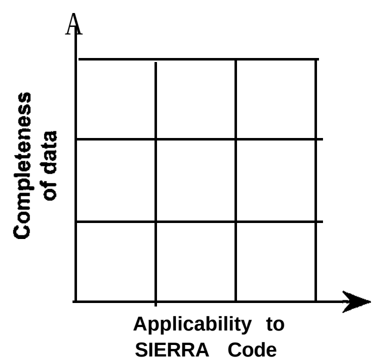
The FABIG web site at http://www.fabig.com provides information on large scale fire effects on steel structures, aimed in particular at safety requirements for offshore structures. The Fire and Blast Information Project sponsored a variety of experimental projects for measuring the effects of large confined and unconfined horizontal and vertical turbulent jet and pool fires. This was a £4,400,000 study sponsored by 10 oil companies and the UK Health and Safety Executive.

All flames were luminous and smokey, and surface radiative emissive power is reported. Data was collected from many sources, including labs in Norway and the UK. In addition, a survey of existing data on pool and jet fires was carried out similar to the present study, with an eye to validation of fire codes.

Data reported for the sponsored studies includes fuel type (crude of various grades), flow rate, pressure, flame geometry, external radiation field, flame surface emissive power and IR emission spectrum, and meteorological conditions.

A mission to Kuwait to investigate the well fires following the Iraqi war reported data on large jet fires, including data on plume geometry and radiative field.

Detailed data and access to the survey of available references can be obtained only through membership in FABIG. The reference is not rated, as the individual reports may only be accessed by membership in FABIG.



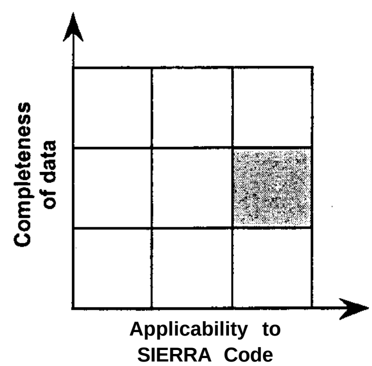
Gregory, J. J., Keltner, N. R., and Mata, R., 1989, "Thermal Measurements in Large Pool Fires," ***Journal of Heat Transfer,*** **Vol. 111, pp. 446-454.**

This paper presents the temperature and heat flux measured at different stations around a large cylindrical calorimeter immersed in a rectangular JP-4 pool fire. The calorimeter is a 6.4 m cylinder with a 1.4 m outer diameter. The dimensions of the pool fire are 9.1 m x 18.3 m. The tests were carried out in a light wind (>5 m/s) resulting in an asymmetric burn.

Flame temperatures were measured using K-type sheathed thermocouples, located at various heights on six water-cooled towers surrounding the calorimeter and at different positions on the calorimeter surface. The error in the thermocouple measurements due to radiation loss from the bead was estimated to range from 4 % to 12 %. Temperature and heat-flux was calculated on the large calorimeter, and on four smaller calorimeters, was determined using a 1-D inverse thermal analysis. Errors in the heat-flux data ranged from 2 % to 17 %.

Reported data include the transient flame temperatures and heat flux at each measurement station, and the average heat flux values at each measurements station for the test series, plotted against the calorimeter surface temperature. The flame temperature measured with the thermocouples is also provided in tabular form.

Because the experiment closely matches the accident scenario of the present study, and the thorough nature of the data and error analysis, this reference would be highly useful for the current project except for the lack of species concentration and velocity data.



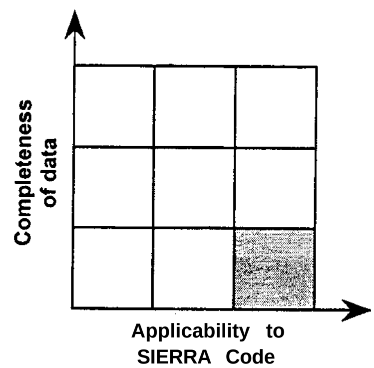
Gritzo, L. A., Gill, W., and Nicolette, V. F., 1998, "Estimates of the Extent and Character of the Oxygen-Starved Interior in Large Pool Fires," from Very Large-Scale Fires, Keltner, N. R., Alvares, N. J., and Grayson, *S.* J. Eds., *ASTM Special Technical Publication 1336,* pp. 84-98.

This paper describes the size, shape, and character of the oxygen-starved interior of a large-scale pool fire. This phenomenon is usually present only in large-scale fires, and is not observed in the majority of small-scale pool fires that dominate the literature. The emphasis of the paper is on the effect this region has on object placement within the pool fire during survivability tests.

The experimental apparatus consists of a 1.8 m diameter JP-4 pool fire in low-wind conditions. The flame temperature is evaluated at seven radial stations and at five heights. (No error estimate is provided.) The majority of the data are presented in the form of a defined variable, given by the product of the mean temperature and the standard deviation of the temperature at a given location, which indicates the presence of the oxygen-starved zone.

A numerical simulation is also carried out using the VULCAN fire field model, and the predicted temperature and fuel concentration fields are presented. Thermocouple errors limit the accuracy of the experimental temperature data and thus prevent direct comparison with the numerical data, but the general trends observed in the pool fire are consistent with the numerical simulation.

The temperature distribution data should prove to be useful for the purposes of this study, especially considering the rarity of large-scale pool fire data. Unfortunately, the experimental error in the thermocouple measurements will likely prevent direct comparison to the SIERRA/FUEGO or SIERRA/SYRINX code results.

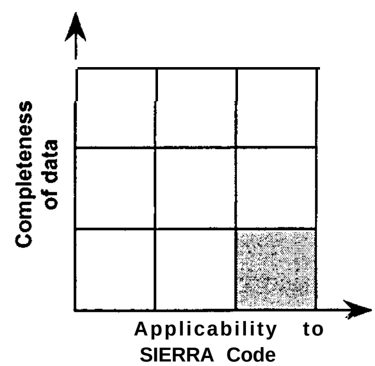


Koseki, H., 1999, "Large Scale Pool Fires: Results of Recent Experiments," Fire Safety Science, Vol. 6., pp. 115-132.

This survey paper presents results of recent pool fire experiments, for the purpose of modeling an accident at an oil refinery. The experiments ranged from lab-scale to full-scale pool fires, and used many different fuels.

The scaling effects of pool fires are demonstrated by plotting flame height, burning rate, and radiative fraction as a function of pan diameter. Other data include a contour plot of temperature within a 6 m heptane pan fire, a table of mass burning rates and n-radiance measured at a single point for four different heptane dike fires, smoke yield as a function of pan diameter for crude oil and heptane fires, the distribution of particle diameters for crude oil pool fires from 0.1 m, 1 m, 12 m circular pans, and a 2.7 m square pan, and the axial temperature distribution as a function of time for crude oil and kerosene pool fires.

Although many experiments are referenced in this survey paper, very little of the presented data is useful. Also, no experimental uncertainty is included with any of the data. Consequently, this paper will be of little use to the present study.



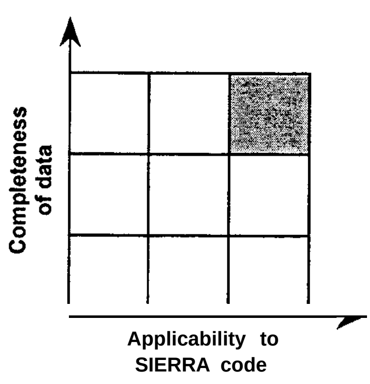
Koseki, H., Iwata. Y., Natsume, Y., Takahashi, T. and Hirano, T., 2000, "Tomakomai Large Scale Crude Oil Fire Experiments," *Fire Technology*, Vol. 36, no. 1, pp.24-38

This paper presents results of large-scale crude oil pool fire experiments conducted at Tomakomai, Japan. The experiments are carried out by burning crude oil that is floating over water in steel pans of three different diameters, 5, 10 and 20 m in an outdoors facility. Comprehensive information about the fuel is presented in the paper in terms kinematic viscosity, density and mass fraction of elements, so that a combustion code can provide the necessary input for a CFD and radiation code. As the experiments are carried out in an outdoors facility relatively rough information is available only in terms of average velocity and direction of the wind.

Irradiance measurements were taken with 12 to 16 wide-angle radiometers located at different radial positions and about 1.2 m above the ground, aimed at the fire axis. The distance between the radiometers and the fire axis was set at L/D = 2 and 3, where L is the distance and D is the pan diameter. Five JR cameras are used to measure the radiative energy from the fire and local radiation and temperature profiles of the flame together with an array of 39 thermocouples. The temperature values measured inside the flame with thermocouples are compared with values obtained through IR camera data.

In order to observe the effects of such a fire on a nearby structure, an adjacent pan is located close to burning pan and the wall and roof temperatures of the adjacent are measured both by thermocouples and JR camera. The distribution of the primary particle diameter of smoke agglomerates is also provided.

This paper will likely be very useful for validating the SIERRA/FUEGO or SIERRA/SYRINX code, since the experiment is very similar to the accident scenario likely to be encountered in the present study. The emphasis of this paper is the macroscopic behavior of the fire, so it would be best suited to evaluating the overall performance of the code, rather than the validation of individual modules.



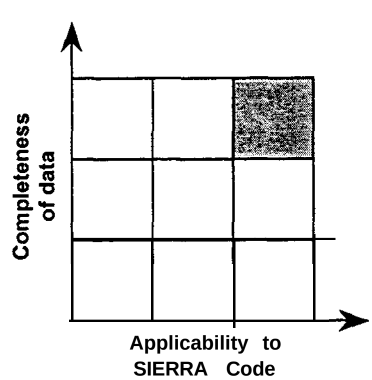
Koseki, H., and Yumoto, T., 1988, "Burning Characteristics of Heptane in 2.7 m Square Dike Fires," ***Fire Safety Science - Proceedings of the Second International Symposium,*** **pp. 231-240.**

This paper presents the characteristics of heptane burning in a 2.7 square dike. Two experiments were performed; the first had four open tank fires on top of the dike fire, while the second was performed using only the square pan. In both cases, a 2.7 m square steel pan was used to contain the pool fire. The open fire tanks were modeled using four 0.8-m diameter cylindrical tanks with a height of 0.4 m, which were located within the square pan. A 3-6 cm layer of heptane was floated over water in the square pan and in the cylindrical tanks. All experiments were carried out in a 24 m × 24 m × 20 m room.

Temperature was measured using an array of 60 K-type thermocouples, located throughout the flame region. The total radiation heat flux from the flame to the surroundings was measured using themopile-detector type radiometers, located at a fixed radial distance from the fire axis. The radiation from horizontal slices of the flame was measured using five narrow-angle radiometers, installed at a fixed radial distance from the flame and at the height of the pan rim. Vertical velocities were measured using seven stainless steel bi-directional pressure probes. The velocity distribution was calculated using the pressure measurements from these probes, and the local density estimated from the temperature measurements. The air entrainment is calculated from the velocity measurements, and by assuming a "top hat" velocity profile. The composition of the products of combustion was determined using a gas chromatograph.

Data include a table of mass burning rates, surface regression velocities, and the total radiation measured at one location away from the center of the dike. Plots include the, temperature contour plots, as well as air entrainment, and oxygen and carbon dioxide concentrations as a function of axial height. Radiation data include plots of irradiance as a function of distance from the flame, and as a function of height above the ground.

This paper will be useful for code validation. The experimental apparatus is relevant to the accident scenario, and the temperature data is quite comprehensive. Unfortunately, only the centerline velocity measurements are included, and the accuracy of these measurements is suspect. Also, no experimental uncertainty is provided.



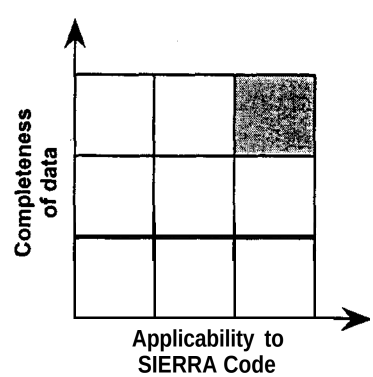
Kramer, M. A., Greiner, M., Koski, J. A., Lopez, C., and Sho-Antila, A., 2001, ('Measurement of Heat Transfer to a Massive Cylindrical Object Engulfed in a Regulatory Pool Fire," Presented at the 2001 ASME National Heat Transfer Conference, Anaheim CA., June 10-12.

This paper presents data to validate numerical simulations of heat transfer to a large object immersed in a pool fire. The experimental conditions conform to USNRC regulations for testing containers used to transport high-level radioactive waste. The apparatus consisted of 3800 kg cylindrical carbon steel calorimeter with a length of 4.6 m and a diameter of 1.2 m. The calorimeter was suspended 1 m above a circular JP-8 pool fire, with a 7.16 m diameter. The fuel floated over a 1 m deep pool of water, and had an initial depth of 12.7 cm. No more was provided during the test, and the test concluded when the fire exhausted itself The entire apparatus was surrounded by a circle of V-shaped wind fences, which minimized the effect of wind on the fire. Wind conditions varied throughout the test, but the ambient wind speed was always less than 2.9 m/s.

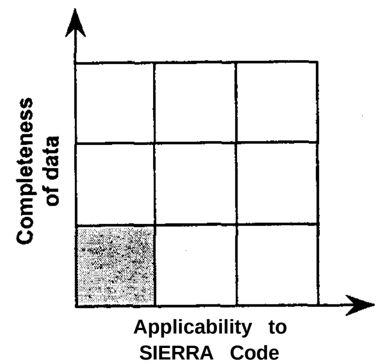
Temperature was measured on the interior surface of the calorimeter using an array of more than forty thermocouples, located at various stations on the inner surface of the calorimeter. The experimental error of the temperature measurements is estimated to be the larger of ±1.1 K or 0.4%, with 95% confidence. Heat flux measurements were determined using the thermocouple measurements in conjunction with the SODDIT 1-D inverse conduction code. The estimated uncertainty of the heat flux measurements is within 10%, at 95% confidence. Eight directional flame thermometers (resulting in 16 directional measurements) are located outside of the calorimeter, and are used to measure the local flame temperatures.

Data include plots of ambient wind speed, flame emissive power, and temperature distribution as a function of time. The axial temperature distribution is also plotted at one instant. The heat flux distribution is also plotted as a function of time.

This paper will prove to be extremely useful for the present study, and should be used to validate the accuracy of the SIERRA/FUEGO or SIERRA/SYRINX code when applied to model a full-sized accident scenario. The purpose of the experiment is to verify a fire code, and the experiment closely matches the accident scenario of interest. In addition, the experimental data is comprehensive in nature, and a thorough error analysis is provided.



Nakos, J. T., Gill, W., and Keltnerm N. R., 1991, "An Analysis of Flame Temperature Measurements using Sheathed Thermocouples in JP-4 Pool Fires," ***Proc, 1991 ASME/JAME Thermal Engineering Conference,*** **March 1991.**



This paper describes the use of sheathed thermocouples to measure the flame temperature in JP-4 pool fires in a variety of test conditions. The pool has a diameter of 2 m, and a 165 x 130 cm steel plate was mounted adjacent to the fuel surface.

The experimental data consists of thermocouple measurements evaluated at eight different locations in a JP-4 pool fire.

The reported data include the temperature measurements from one thermocouple, and the differences between the measurements of the other thermocouples, in order to document the effects of thermocouple bead emissivity, orientation, and shielding. No error analysis is included.

The paper does not intend to describe the temperature field in the pool fire, and generally the data is presented in a manner that renders it unsuitable for the current application.

Russell, L. H., and Canfield, J. A., 1973, "Experimental Measurement of Heat Transfer to a Cylinder Immersed in a Large Aviation-Fuel Fire," *Journal of Heat Transfer*, Vol. 95 C, pp. 397-404.

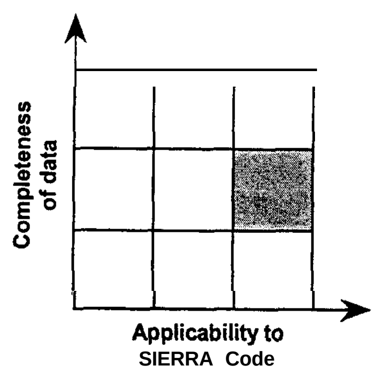
This paper consists of two parts: the first presents the temperature and total radiant flux of a rectangular JP-5 pool fire, and the second presents the temperature distribution across the outer shell of a cylinder immersed in the fire at various locations. The pool was rectangular, with dimensions of 8 ft x 16 ft.

The temperatures were measured using shielded chromel-alumel thermocouples, and the radiant flux was measured using a narrow-angle Gardon-type gauge. The first test, evaluating the temperature and radiant heat-flux distributions within the fire, was carried out in quiescent conditions. The reported data consists of contour maps of temperature and total-radiant heat flux. The error in the temperature and radiant heat-flux data was 6 % and 30 %, respectively.

The cylinder used for the second part of the test was composed of 304 stainless steel, with a soot-coated surface having an emissivity approaching unity. The cylinder consisted of a core surrounded by an insulating layer and an outer layer. Four sets of three thermocouples were located within the outer layer, at different depths from the outer surface. The four sets were angularly removed from each other by 90°. The insulated layer resulted in an adiabatic boundary condition on the inner surface of the outer layer.

The cylinder apparatus was placed roughly in the center of the fire. For this experiment, a 1 mph wind was blowing, resulting in an asymmetrical flame. The experimental results consist of the temperature profiles through the outer layer of the cylinder, and the effective heat transfer coefficient, calculated by solving an inverse conduction problem. The error in the temperature measurement is less than 6%.

This paper should prove extremely useful for code validation because of the completeness of the data, the detailed error analysis, and the relevance of the experimental apparatus to the present application. However, no concentration or velocity profile data are given.



MOMENTUM-DRIVEN DIFFUSION FLAMES

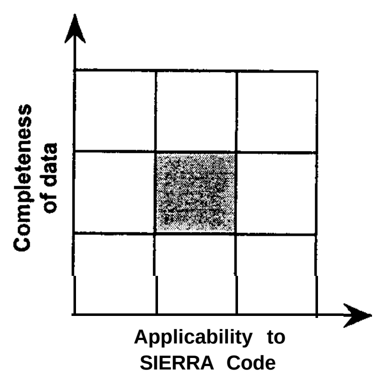
Bennett, B. A., McEnally, C. S., Pfefferle, L. D., and Smooke, M. D., 2000, "Computational and Experimental Study of Axisymmetric Coflow Partially Premixed Methane/Air Flames," *Combustion and Flame,* Vol. 123, pp. 522-546.

The purpose of this paper is to study the effect of premixing methane/air diffusion flames. This is done both computationally and experimentally. The experimental apparatus consists of an inner cylindrical burner jet with an inner radius of 0.555 cm, surrounded by an outer annular jet. The premixed fuel and primary air passes upward through the inner jet, where it is simultaneously ignited and exposed to the secondary air, traveling upwards through the outer annular jet. Six different flamed are studied, having equivalence rations ranging from $\Phi \rightarrow \infty$ (no premixing) to $\Phi = 2.464$. The Reynolds numbers range from 3 1 ($\Phi \rightarrow \infty$) to 167 ($\Phi = 2.464$), which are all within the laminar regime.

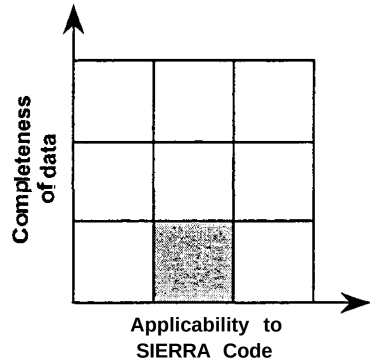
Gas temperatures are measured using uncoated thermocouples. Species concentrations are determined by extracting gas samples and analyzing them using online mass spectrometry. In particular, species concentrations of methane, formaldehyde, acetylene, oxygen, water, carbon dioxide, as well as C_2H_2O and other higher hydrocarbons are measured. The experimental uncertainty is described in detail; temperature measurements have an absolute uncertainty of 50 K and a relative uncertainty of 10 K, and a spatial resolution of 0.3 mm. The concentrations of methane, acetylene, oxygen, water, and carbon dioxide have absolute uncertainties of 30%. Measurements of formaldehyde and other higher hydrocarbons have relative uncertainties of 30% and absolute uncertainties up to three times higher. All flow rates are accurate to within 5%. Quantities derived from the flow rates are accurate to within 10%.

Experimental data include maximum flame temperature tabulated for each equivalence ratio, and graphs of temperature as a function of axial position. The mole fractions of CH_4, O_2, H_2O, CO_2, CO, Hz, OH, C_2H_2, and C_2H_2O are also plotted as a function of axial position. This paper also presents the results of a computational simulation, which are quite comprehensive in nature. In general, the numerical results were in good agreement with the experimental data.

This paper will prove particularly useful for validating the chemistry module of the fire code, because of the large number of species considered, and the detailed error analysis. It may also be useful to compare the results obtained with the fire code to the numerical simulation in this work. Radiant heat flux and the velocity field are not measured in this experiment.



Delichatsios, M. A., and Orloff, L., 1988, "Effects of Turbulence on Flame Radiation from Diffusion Flames," *Proc. 22nd Symposium (International) on Combustion,* The Combustion Institute, pp. 1271-1279.



This paper discusses the effect of turbulence on soot formation and radiation heat transfer. The experimental apparatus consists of a nozzle that discharges fuel vertically upwards into the flame. A small coflow of oxygen is used to attach the flame to the nozzle exit. Burner diameters of 1 mm, 1.5 mm, 2 mm, 3 mm, and 4 mm were used. The entire apparatus is surrounded by a water-cooled enclosure. Flames of C_2H_2, C_3H_6, CH_4 were studied.

Total flame radiation is measured using a wide-angle radiometer. Radiation per unit flame height was measured using two slit-radiometers. No experimental uncertainty is provided with any of the measurements.

Data include plots of turbulent radiant fractions (the ratio of total radiant power to the theoretical heat release rate) as a function of total heat release rate, dimensionless radiant power per unit height as a function of dimensionless height, and radiant fraction as a function of several different dimensionless scales.

Although radiation data is presented, this paper is of limited use to the present study because no error analysis is given, radial variation of properties are not provided, the non-dimensional presentation of the data is inconvenient for validation, and no other data (i.e. the temperature field, velocity field, and turbulence statistics) are provided.

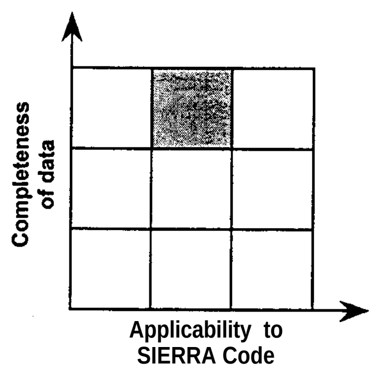
Faeth, G. M., Gore, J. P., Chuech, S. G., and Jeng, S. M., 1989, "Radiation from Turbulent Diffusion Flames," from *Annual Review of Numerical Fluid Mechanics and Heat Transfer Vol.* 2, Tien, C. L. and Chawla, T. C. Eds., Hemisphere Publishing Corp., New York, U. S. A., pp. l-37.

This work presents the radiation properties of luminous and non-luminous turbulent diffusion flames. It contains no original experimental data, but presents a collection of results from six published sources. The flames studied included H_2 (*Re* = 3000 and 5722), CO (*Re* = 11400, 7475, and 13140), CH_4, (*Re* = 2920, 5850, 11700, and 4.6-5.0 $\times 10^6$), and C_2H_4 (Re = 6370 and 12740.) In all cases, the diffusion flames were formed by injecting the fuel upward through a vertical burner tube. With one exception, all flames were in still air, at normal temperature and pressure.

A considerable amount of data is presented in this work. Data include plots of the mass fraction of combustion products as functions of equivalence ratios for H_2/air and C&/air diffusion flames, soot volume fraction as a function of equivalence ratio for a C_2H_4/air diffusion flame, mole fractions, temperature, and velocity as a function of axial distance for a CO/air diffusion flame, and mass fraction and temperature as a function of axial distance for a CH_4/air diffusion flame. Radiation measurements include spectral radiation intensity plots for all types of flames, and total radiation heat flux as a function of axial distance for a CH_4/air diffusion flame.

This paper contains few details of experimental apparatus and no information about error and uncertainty, but these details can be found in the cited references.

This paper should prove to be useful for code validation because of the comprehensive quality of the data, and because many different fuel types are considered. This paper also contains an excellent summary of the available experimental data for turbulent diffusion flames up to that time.



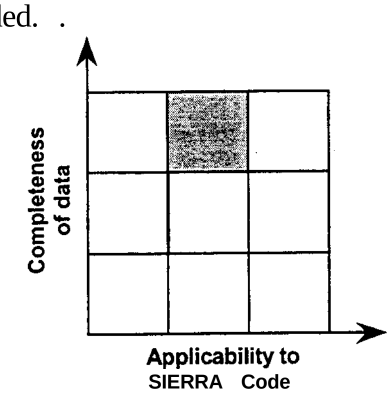
Faeth, G. M., Gore, J. P., and Sivathanu, Y. R., 1988, "Radiation from Soot-Containing Flames," from *Proceedings of AGARD Conference No. 422 Combustion and Fuels in Gas Turbine Engines,* North Atlantic Treaty Organization, pp. 17-l-17-11.

The purpose of this paper is to present the radiation properties of turbulent, soot-containing, luminous diffusion flames. Four flames were studied; two were fueled with ethylene with Reynolds numbers of 6,3 17 and 12,740, and two were fueled with acetylene with Reynolds numbers of 5,300 and 9,200. The fuel flows upwards through a burner passage with an exit diameter of 5 mm. The fuel is then ignited, and the flame is attached with a small coflow of hydrogen. The entire apparatus is contained within a screened enclosure to minimize the effects of ambient drafts.

Data include plots of the mole fractions and mass fractions of the combustion products as a function of equivalence ratio and soot volume fraction as a function of mixture fraction. The mixture fraction, mole fractions and velocity fluctuations are plotted as a function of axial location. Radial variations of soot volume fractions and monochromatic transmittncies (at 632.8 and 5 14.5 nm) are plotted at different axial locations, and radiant heat flux is plotted as a function of axial position. Also, spectral radiation intensities measured at the axis of the flame are plotted at three different axial heights.

Velocity measurements were made with a Doppler anemometer, and had uncertainties less than 5% with 95% confidence. Gas species concentrations were measured using a gas chromatograph. Uncertainties in species concentrations were less than 15% in the flaming region (95% confidence) but were higher in the over-fire region. These measurements were in turn used to calculate mixture fractions, which had uncertainties of -20, -50, and -100% at $f = 0.04$, 0.004, and 0.0005, respectively. Extinction measurements were made using lasers at 514.5 and 632.8 nm, and were used to calculate the soot absorptivitiy and volume fraction. These measurements had uncertainties of less than 10% and 20%, respectively. Spectral radiation intensities were measured using a monochromator, with a view angle of 1.2°, and radiation heat fluxes were measured using a wide-angle (150°) water-cooled radiometer. Uncertainties in these measurements were less than 15% and 10%, respectively.

This paper may prove to be very useful for validating the radiation and chemistry modules of the SIERRA/SYRINX code, since the combustion products composition and radiation intensity are described in detail and an extensive error analysis is provided. .



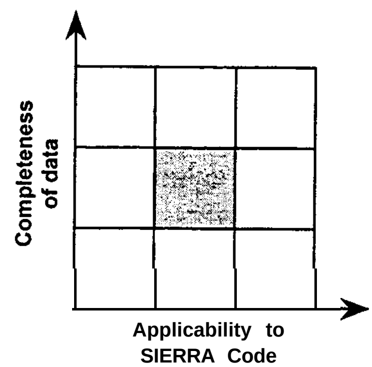
Gore, J. P., and Faeth, G. M., 1986, "Structure and Spectral Radiation Properties of Turbulent Ethylene/Air Diffusion Flames," ***Proc. 21th Symposium (International) on Combustion*****, The Combustion Institute, pp. 15214531.**

This paper describes an experimental and theoretical study of the structure and properties of two round, turbulent, luminous ethylene/air diffusion flames, with Reynolds numbers of 6,370 and 12,740 at the burner exit. The apparatus is contained within a screened enclosure, to minimize the effects of ambient drafts.

Data include mean and fluctuating velocities, concentrations of the combustion products, and soot volume fractions. Extensive thermal radiation measurements are also presented, including the absorption at 632.8 nm measured through the diameter of the flame, the spectral intensity distribution measured at different heights above the flame, and the radiant heat flux at different axial and radial distances from the flame axis.

Velocity measurements are made using a laser Doppler anemometer. Uncertainties in both mean and fluctuating velocity components are less than 5%. Uncertainties in species concentrations are less than 15%. Soot absorption and volume fraction is determined using a laser. Uncertainties in extinction coefficient and soot volume fraction measurements are less than 10% and 20%, respectively. Spectral intensities and radiation fluxes have uncertainties of less than 15% and 10%, respectively.

This paper will prove quite useful because of the breadth and quality of data provided, and the detailed error analysis. The paper will be particularly useful for validating the radiation module of the code, since extensive radiation data is provided.



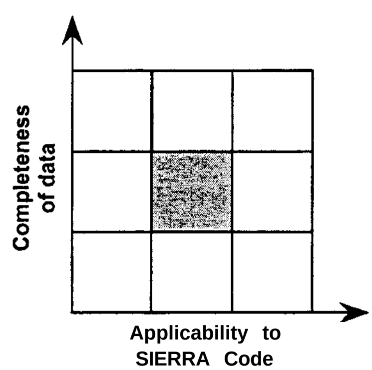
Gore, J. P., Faeth, G. M., Evans, D., and Pfenning, D. B., 1986, "Structure and Radiation Properties of Large-scale Natural Gas/Air Diffusion Flames," *Fire and Materials*, Vol. 10, pp. 161-169.

This paper describes the flame structure and properties of a large-scale turbulent natural gas/air diffusion flame. The experimental apparatus consists of a burner injecting natural gas (about 95% methane by volume) into still air. Two different burners were used, with inner diameters of 76 and 102 mm. Seven different flames, with chemical energy release rates ranging from 135 to 210 MW were studied, all having Reynolds numbers near 3 x 10^6. The tests were conducted outdoors, with ambient wind speeds ranging from 0.2 to 2.1 m/s.

Temperature measurements were made using an array of 20 thermocouples, and radiant heat flux was measured using five water-cooled heat flux transducers, located at various positions throughout the experiment. The locations and orientations of these radiometers are provided in detail. One radiometer had a view angle of 7°, while the other had view angles of 150". Total radiation fluxes are found by integrating spectral radiation intensities over all wavelengths and paths through the flame. The concentrations of N_2, O_2, CO, H_2O, and H_2 were measured using a gas chromatograph.

Data include plots of the mass fraction of each species as a function of fuel equivalence ratio, mean temperature measurements along the axis of the flame, and the spectral radiation as a function of wavelength measured at one axial station. The total radiation heat flux evaluated at different detectors for two different flames is presented in tabular form. No experimental uncertainty analysis is provided, although thermocouple errors were estimated to have caused the mean temperatures to be over-measured by 10 K in the flame region. Richardson extrapolation suggests that discretization errors in total heat flux calculations are less than 10%.

This paper should prove quite useful for validating the radiation module of the SIERRA/FUEGO or SIERRA/SYRINX code, because of the comprehensive nature of the radiation measurements. Although the experimental uncertainty is not provided, good agreement between the data and predicted results as well as the results from other published sources suggest that the data is generally of a good quality. Unfortunately, the velocity and temperature distributions in the fire are not provided.



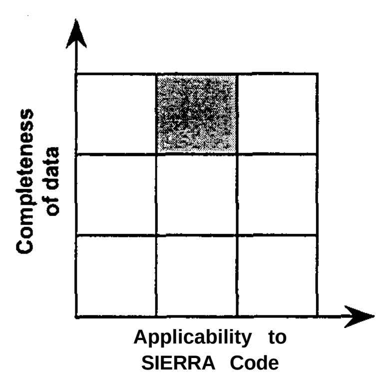
Gore, J. P., Jeng, S. –M., and Faeth, G. M., 1987, "Spectral and Total Radiation Properties in Hydrogen/Air Diffusion Flames," ***Journal of Heat Transfer,*** **Vol. 109, pp. 165-171.**

This paper describes the structure and radiation properties of hydrogen diffusion flames. The apparatus consists of a 5 mm diameter water-cooled burner that injects hydrogen vertically upward, where it is ignited. The burner and flame are contained within a 115 mm diameter quartz tube, which in turn was contained within a screened enclosure to minimize the effects of drafts. A coflow of air is used to attach the flame to the burner exit. Two flames were studied, with Reynolds numbers of 3000 and 5720 at the burner exit.

Presented data include plots of the mass fraction of the combustion products as a function of the equivalence ratio and also the mole fractions of combustion products, mean temperature, velocity, and velocity fluctuations along the fire axis as a function of height. Radiation data include spectral radiation intensities for radial paths through the axis measured at three different heights and total radiative heat fluxes, measured at the centerline and plotted as a function of height, and measured at the burner exit plane, and plotted as a function of radial location.

Velocity measurements were made using a laser Doppler anemometer. Uncertainties in mean and fluctuating velocity measurements were less than 5%, with 95% confidence. Temperatures were measured using a thermocouple; no uncertainty is specified, but the data are not adjusted for radiation losses from the bead so the measurements are thought to be 100-200 K too low in the hottest parts of the flame. Species concentrations were measured using a gas chromatograph; these measurements have uncertainties of less than 15%. Spectral radiation intensities were measured using a narrow-angle (1.2") monochromator with a pyroelectic detector, and total heat flux measurements were made using a wide-angle (150°) sensor. Uncertainties in these measurements are less than 20% and 10%, respectively.

This paper will be extremely useful for validating the SIERRA/FUEGO or SIERRA/SYRINX code. The radiation data is very comprehensive, and the velocity and temperature fields are also well specified. Since these types of flames are non-luminous, this data will be particularly useful for validating the performance basic radiation code without soot effects.



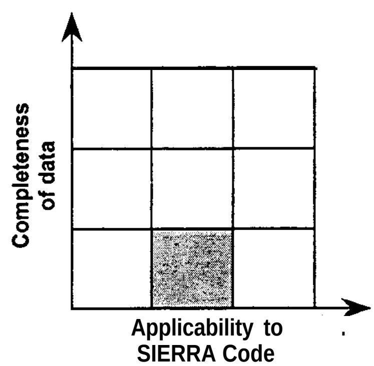
Gülder, Ö, 1992, "Soot Formation in Laminar Diffusion Flames at Elevated Temperatures," *Combustion and Flame,* Vol. 88, pp. 74-82.

The purpose of this paper is to determine the influence on flame temperature on soot formation for different fuels. The experimental apparatus consists of a 3 mm diameter stainless steel burner tube, which is concentrically located within a 100 mm diameter converging air nozzle. Both the fuel and air streams are preheated by electric resistance heaters. The fire was contained in a flame enclosure with glass windows, which provides optical access while eliminating the effects of ambient drafts. Data from twenty different laminar flames are presented, each with a different combination of fuel preheat temperature and mass flow rate. The fuels were Ethylene, Propylene, Isooctane, and Propane, although the Propane flame data was taken from previously published source.

Line-of-sight soot volume fractions are calculated based on the transmission of a multilane laser beam, at wavelengths of 830 nm, 632.8 nm, and 515 nm. The optical path length (flame diameter) was determined optically, using a reading telescope. These measurements had an uncertainty ranging between 0.125 and 0.25 mm, or less than 1%. soot brightness temperature was determined using a dual-wavelength disappearing filament pyrometer. The temperature uncertainty at calibration was ±15 K.

Presented data include a table documenting the reactant temperature, fuel mass flow rate, smoke point height, line-of-sight maximum soot volume fraction, adiabatic equilibrium temperature, and the maximum line-of-sight soot surface temperature for each flame. Plots of soot volume fraction and soot temperature as a function of height above the burner at different preheat temperatures are also included.

Although momentum-driven diffusion flames are not expected to be encountered in the accident scenario, simulating these experiments shall prove to be especially useful for validating soot properties since the temperature and soot-volume fractions in these flames is well documented. Unfortunately, the radiant intensity and velocity fields are not measured.



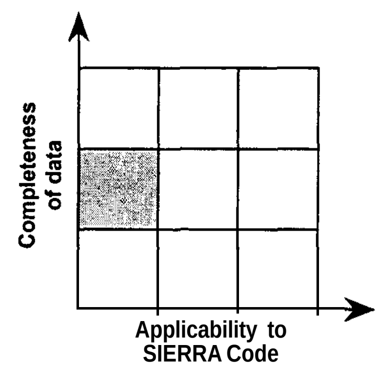
Gülder, 0. L., Thompson, K. A., and Snelling, D. R., 2000, "Influence of the Fuel Nozzle Material on Soot Formation and Temperature Field in Coflow Laminar Diffusion Flames," ***Proceedings, Com bustion Institute Canadian Section, Spring Technical Meetings, Ottawa ON.***

This paper describes the effect of fuel nozzle material on the properties of a momentum-driven diffusion flame. The experimental apparatus consists of a 10.9 mm diameter fuel tube, centered in a 100 mm diameter air nozzle. Fuel tubes made of aluminum, steel, and Pyrex glass were studied. The fuel and air are discharged into a screened enclosure and ignited. Two different fuels, ethylene and propylene, are studied. The ethylene and propylene have flow rates of 194 ml/min and 40 ml/min respectively, and the air has a flow rate of 284 l/min.

The fuel tube temperature is measured using two thermocouples. Radiant intensity is measured with a spectrometer. No experimental uncertainties are included for these measurements. Soot temperature and volume fraction is calculated from the spectral intensity measurements.

Data include plots of radial soot volume fraction profiles and soot surface temperature profiles, evaluated at eight axial stations for the propylene flame and six axial stations for the ethylene flame.

This paper may be used to validate the soot chemistry module of the SIERRA/FUEGO or SIERRA/SYRINX code, since the soot temperature and volume fraction distributions are well characterized. Unfortunately, no experimental uncertainty is reported, and although spectral intensity was measured to calculate the soot properties, the intensity values are not reported in the paper.



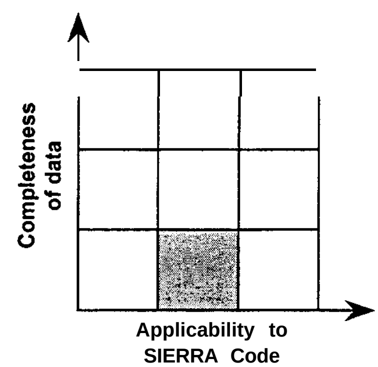
Jeng, S. M., and Faeth, G. M., 1984, "Species Concentrations and Turbulence Properties in Buoyant Methane Diffusion Flames,'" *Journal of Heat Transfer,* Vol. 106, pp. 721-727.

This paper presents the species concentrations and turbulent statistics for a turbulent, buoyant, methane diffusion flame. The turbulence data is then used to evaluate different turbulence modeling procedures. The experimental apparatus consists of natural gas (-95% methane by volume) being injected upward through a liquid-cooled burner having an exit diameter of 5 mm. The flames are attached to the burner by a small coflow of hydrogen. The entire apparatus is contained within a screened enclosure to minimize drafts. Three different flames with exit Reynolds numbers of 2920, 5850, and 11700, were studied.

Data include plots of species mass fraction as a function of fuel equivalence ratio, temperature and species distributions along the flame axis, and radial variation of temperature and species concentration, measured at three axial locations. Turbulence statistics include radial distributions of Reynolds stress and velocity fluctuations, evaluated at four axial locations.

Mean and fluctuating velocities were measured using a laser Doppler anemometer; these results have an experimental uncertainty of less than 10%. Species concentrations are measured using a gas chromatograph. Uncertainties in composition measurement were estimated to be less than 15%. Temperature measurements are made using small thermocouples, but details on the measurements and uncertainty analysis are not provided.

This paper will be moderately useful for the present study. Although turbulence modeling is not the main emphasis of the study, this paper will be useful for validating the turbulence module of the fire code. The temperature profile within the flame is also reported in detail, especially for the *Re = 2920 case.* Unfortunately, this paper does not contain any radiation measurements, and although the mean velocity profile was measured experimentally, it is not explicitly reported in this study.



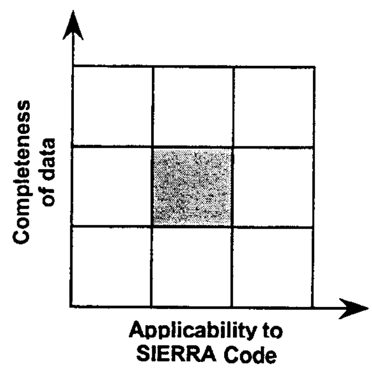
Jeng, S. M., and Faeth, G. M., 1984, "Radiative Heat Fluxes near Turbulent Buoyant Methane Diffusion Flames," *Journal of Heat Transfer*, Vol. 106, pp. 886-888.

The purpose of this technical note is to evaluate methods for predicting total radiant heat fluxes from buoyant, turbulent diffusion flames, by comparing the model predictions with experimental data. The experimental apparatus consisted of a 5mm burner injecting vertically upward into still air. Flames were attached to the burner using a small coflow of hydrogen. Three flames, with Reynolds numbers of 2920, 5850, and 11700, were studied.

Total radiation measurements were made using a wide-angle (150°) gas-purged, water-cooled sensor. The experimental uncertainty of heat flux measurements was less than 10%.

Data include the total radiative heat flux plotted as a function of axial height measured parallel to the flame axis at a radial distance of 575 mm, and the radial distribution of total radiative heat flux measured at the flame base.

This paper should prove useful for validating the radiation module of the SIERRA/FUEGO or SIERRA/SYRINX code, since total radiant heat transfer is the quantity of interest in the present study. Moreover, the experimental apparatus and location of the sensors is well defined, and should be relatively easy to model. Unfortunately, the velocity and temperature distributions in the flame region are not provided.



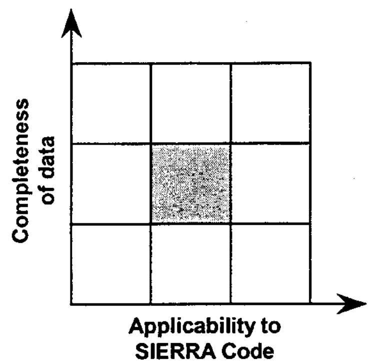
Jeng, S. M., Chen, L. D., and Faeth, G. M., 1984, "Nonluminous Radiation in Turbulent Buoyant Axisymmetric Flames," *Combustion Science and Technology*, Vol. 40, pp. 41-53.

The purpose of this paper is to develop and evaluate methods for predicting radiation from turbulent buoyant flames. The experimental apparatus consisted of a methane diffusion flame injected vertically upward from a water-cooled burner with an exit diameter of 5 mm. The burner apparatus is contained in a screened enclosure to ensure still-air conditions. Three methane flames were studied, having Reynolds numbers of 11700, 5850, and 2920.

Spectral radiance measurements were made using a monochromator and a pyroelectric detector. Radiance measurements were made at wavelengths between 1.5-2.6 □m.

Data include spectral radiation intensities measured at three different axial stations for the flame with *Re* = 11700 and two different axial stations for the flame with *Re* = 2920. Graphs of mean temperature and species concentrations as a function of axial position are also plotted for the *Re* = 5850 flame, although it is not clear how these properties were measured. No error estimate of the data is provided, but the results are in reasonably good agreement with models based on mean properties.

This paper is of limited utility because no error analysis is included, and no measurements were taken off the fire axis. Nevertheless, this paper might be useful for validating a spectral radiation analysis. Since this type of flame does not produce much soot, this data can be used to verify that the effects of CO, CO_2, and H_2O combustion products on the emitted radiation spectrum are being simulated correctly by the fire code. Unfortunately, the velocity distribution in the flame is not presented.



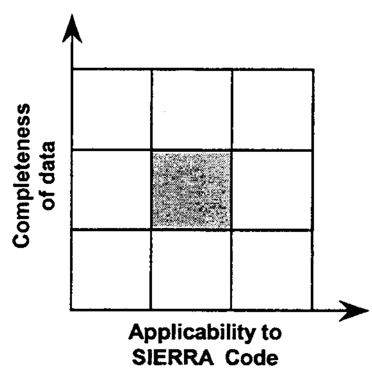
Jeng, S. M., Chen, L. D., and Faeth, G. M., 1982, "The Structure of Buoyant Methane and Propane Diffusion Flames," ***Proc. 19th Symposium (International) on Combustion*****, The Combustion Institute, pp. 349-358.**

This paper documents the structure of a turbulent, axisymmetric methane diffusion flame in still air with significant buoyant effects. Case studies consisted of propane flames with Reynolds numbers of 5890, 11780, and 23560, and methane flames with Reynolds numbers of 2920, 5850, and 11700. The apparatus consists of an upward-oriented burner with a diameter of 1.194 mm and 5 mm for methane and propane fuels, respectively. In both cases, the flame was attached to the burner with a small coflow of hydrogen. The entire apparatus was located within a screened enclosure to minimize the effects of ambient drafts.

The mean and fluctuating velocities were measured using a Doppler anemometer and temperature was measured using a thermocouple array. The radiant heat flux was measured using a gas-purged, water-cooled sensor.

Reported data include graphs of the mean velocity, velocity fluctuation, and temperature variation along the flame axis, as well as the radial profiles of mean temperature, mean velocity, and velocity fluctuations at six axial locations. Also included is the total radiation heat transfer from the flame, which is obtained by integrating radiant heat flux measurements taken at different locations around the circumference of the flame. Unfortunately, these discrete measurements are not included. Although there is no formal error analysis, the results of this study are in good agreement with a previous experimental study and with a numerical model.

This paper should prove to be moderately useful for code validation. The velocity and temperature fields in the fire are described in detail, and the radiation module can be verified by comparing the total radiant loss from the flame to the experimental data.



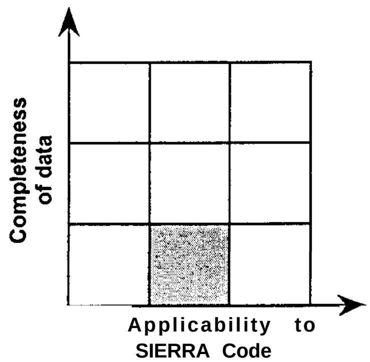
Kennedy, I. M., Yam, C., Rapp, D. C., and Santoro, R. J., 1996, "Modeling and Measurements of Soot and Species in a Laminar Diffusion Flame," ***Combustion and Flame,*** **Vol. 107, pp. 368-382.**

This paper proposes a new analytical model for laminar, soot-laden flames, which is evaluated by a comparison with experimental data. The experimental apparatus consists of a coaxial laminar ethylene-air burner, consisting of an 11.1 mm diameter brass fuel tube, surrounded by a 102 mm diameter air channel. The flame was shielded by a brass cylindrical chimney to minimize the effects of ambient drafts. The volume flow rates of the ethylene and air were 3.85 cm^3/s and 713 cm^3/s, respectively.

The composition of the combustion gases was determined using a mass spectrometer, and were independently verified by gas chromatography analysis. Both of these techniques yielded agreements within ±20%. Laser-induced florescence was used to measure the OH concentration field. These measurements were obtained from a previous study. Temperature, velocity, and soot volume fraction data is included from other published sources.

Reported data include the radial velocity, temperature, C_2H_2 and OH mole fraction profiles at two axial positions, the soot volume fraction along the axis plotted as a function of height, the radial distribution of soot volume fraction at four axial locations.

This paper may prove somewhat useful in the present study, especially for verifying the chemistry module of the SIERRA/FUEGO or SIERRA/SYRINX code. Also, the temperature and velocity distributions are reasonably well documented. The applicability of this study is limited, however, since momentum diffusion flames are unlikely to be encountered in the code application.

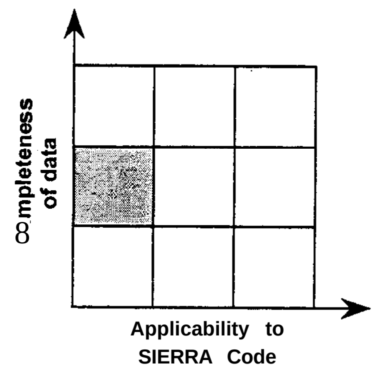


Liu, F., Guo. H., Smallwood, G.J. and Gülder, Ö., 2001, "Effects of Gas and Soot Radiation on Soot Formation in a CoFlow Laminar Ethylene Diffusion Flame," in *Radiation III: Third International Symposium on RadiativeTransfer*, M. Pinar Mengüç and N. Selcuk, eds., Begell House, New York, 2001.

This paper is chiefly concerned with developing a complete numerical model of radiation from sooting flames in which gas radiation is also present, and comparing the relative effects of soot radiation and gas radiation on temperature and soot profiles. In developing the numerical model, however, comparison is made between predictions of the model under various degrees of approximation of the radiative processes and experimental measurements of a carefully controlled laminar diffusion flame. The experimental results are from another source (Guilder et al., 2000), which is also included in this summary.

Presented data include temperature and soot volume fractions presented as a contour plot over the entire domain of the flame. These results are compared with the results of various simulations. No experimental uncertainty is specified for the data.

The results from this paper are somewhat useful for the present application, although it contains no radiation or velocity measurements. Also, the data is presented in a graphic form that makes direct quantitative comparison to other results very difficult. Nevertheless, the soot data is quite comprehensive, and this paper may be used to validate the soot-chemistry module of the SIERRA/FUEGO or SIERRA/SYRINX code.



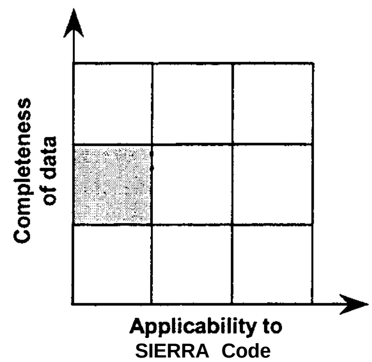
Markstein, G. H., 1977, "Scaling of Radiative Characteristics of Turbulent Diffusion Flames," ***Proc. 16th Symposium (International) on Combustion,*** **The Combustion Institute, pp. 1407-1419.**

This paper presents scaling laws for the radiation properties of propane diffusion flames. The experimental apparatus consists of a 19.06 mm diameter vertical tube, terminated by a 12.7 mm nozzle. Propane (95% purity) was passed through the burner and ignited. Twelve different flames were studied, with fuel flow rates ranging from 44 to 412 cm^3/s.

Two radiometers were used to measure radiation from the fire. The total radiative flux is measured using a wide-angle radiometer. The total flux received from a thin horizontal slice of the fire is also measured by placing a slit aperture over the lens of the wide-angle radiometer. The intensity is measured using a horizontal beam radiometer. Both radiometers were aimed so their horizontal optical axes intercepted the vertical axis of the fire. The radiometers were traversed in the z-direction in order to measure the variation of heat flux and intensity with height. No experimental uncertainty is specified for the data.

Data include plots of the total radiative power as a function of fuel flow rate and radiative power per unit height and intensity as a function of height, plotted for three different fuel flow rates. The last two properties are also plotted in dimensionless form for all twelve-flow rates.

This paper should prove somewhat useful for validating the radiation module of the SIERRA/FUEGO or SIERRA/SYRINX code, since the radiation properties of the fire in the axial direction are well characterized. Unfortunately, no measurements of property variation in the radial direction or temperature and velocity data are reported. Also, the fires are characterized entirely by the fuel flow rate; no other data, such as the exit Reynolds number, is given. This may make computer modeling of the fire difficult.



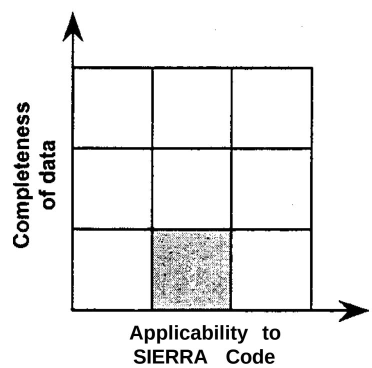
Mbiock, A., Teerling, J., Roekaerts, D., and Merci, B., "Application of the BEM and Analysis of the Role of Radiation Effects in Labscale Turbulent Diffusiuon Flames," in *Radiation III: Third International Symposium on RadiativeTransfer*, M. Pinar Mengüç and N. Selcuk, eds, Begell House, New York, 2001.

The purpose of this report is to demonstrate the influence of radiation in lab scale turbulent diffusion flames, and to demonstrate the superiority of using the Boundary Element Method over performing an optically thin radiation analysis, for predicting the properties of these flames. The experimental apparatus consisted of a 7.2 mm diameter nozzle with a 18.2 mm diameter pilot. The nozzle is surrounded by an annular coflow tube. A mixture of 25% CH_4 and 75% air is passed through the nozzle, while a lean premix of C_2H_2, H_2, air, and CO_2 is passed though the pilot tube. Air flows through the coflow annulus with a velocity of 0.9 m/s.

The mixture fraction, temperature, and species concentrations were obtained using a Roman/Raleigh/LIT technique at 16 locations along the jet axis. A wide-angle radiometer measured the total incident radiation at one location in an attempt to characterize the radiant fraction. No error analysis is provided.

Data include plots of velocity, mixture fraction, and temperature as a function of axial location.

This reference may prove useful for validating the SIERRA/FUEGO or SIERRA/SYRINX code, although the experimental apparatus is not well defined in the paper, which may make modeling difficult. (A more detailed description may be available in one of the references.) Also, the, flame properties are not measured off the fire axis, and no uncertainty analysis is provided.



Sandia-Livermore website with Data Archive: http://www.ca.sandia.gov/tdf/Workshop/DatDwnld.html

A Workshop was organized to to identify experimental data sets on turbulent nonpremixed flames that are considered to be reasonably complete, accurate, and appropriate for the purpose of validating state-of-the-art combustion models, with particular attention to fundamental issues of turbulence-chemistry interaction. The data sets listed are considered to be useful because they include both detailed scalar measurements (temperature, major species, and some minor species) and velocity measurements in the flames with relatively simple geometries, simple fuels, and well defined boundary conditions.

In making these data available to the combustion community, the organizers and contributors have made an effort to provide complete documentation. This documentation should include information on experimental uncertainties. Data sets include:

- Nonreacting Jet of Propane into Air (Sandia)
- H2 and H2/He Jet Flames (Sandia/ETH Zurich)
- H2/N2 Jet Flames (TU Darmstadt)
- H2/N2 Jet Flames (DLR Stuttgart)
- CO/H2/N2 Jet Flames (Sandia/ETH Zurich)
- CH4/H2/N2 Jet Flame (DLR Stuttgart/TU Darmstadt/Sandia)
- NEW Scalar data (28 Apr 2000)
- Piloted Jet Flames:
- Piloted CH4/air Flames (Sandia/TU Darmstadt)
- TNF3, TNF4 & TNF5 Targets
- Piloted Natural Gas Flames (TU Delft/Sandia)
- TNF3 Target
- Piloted Flames of Various Fuels (USydney/Sandia)
- Bluff Body Flames:
- CH4/H2 Flames (USydney /Sandia)
- TNF3, TNF4 & TNF5 Target
- Bluff Body Flames of Various Fuels (USydney/Sandia)
- Swirl Flames:
- Tecflam Swirl Burner
- TNF5 Target

There are some data sets listed (but not linked) that have not been used as targets in these first rounds of workshop activity but may be of interest.

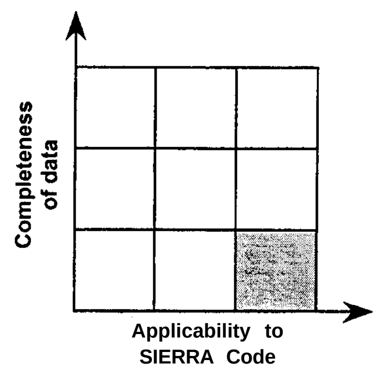
Sivathanu, Y. R., Gore, J. P., 1993, "Total Radiative Heat Loss in Jet Flames from Single Point Radiative Flux Measurements," ***Combustion and Flame*****, Vol. 94, pp. 265-270**

This paper focuses on developing a method for estimating total radiant output of turbulent jet flames based on the measurement of radiative heat flux at a single location. The measurements of heat flux are carried out along the base of the cylinder at the exit plane of the burner and parallel to the axis of the flame until the radiative flux decreases to the low measurement limit of the gauge.

The measurements mentioned in this study are complementary to the ones in referenced dissertations in the studies by Gore (1986), Sivathanu (1990), Dolinar (1992) and Skinner (1991). The new measurements of radiative heat flux at a radial distance to flame height ratio of 0.5 are performed for six different flames with fuels CH4, C2H2 and C2H4.

Measurements and predictions of radiative heat flux at the radiometer location to the amount of radiative energy lost to the environment is presented as a function of height of detector above injector exit parallel to the axis of jet to visible flame length ratio for a fixed value of detector distance radially outward along the exit plane of the burner to visible flame length ratio. Some additional information from the dissertations mentioned above is also tabulated.

This study briefly adds on some additional data to the existing data presented in the dissertations, which could be really helpful for providing detailed experimental data for validation purposes. The data presented here is not complete as it is, as the authors do not present confidence limits; together with the dissertations it might be valuable to provide some addition information.



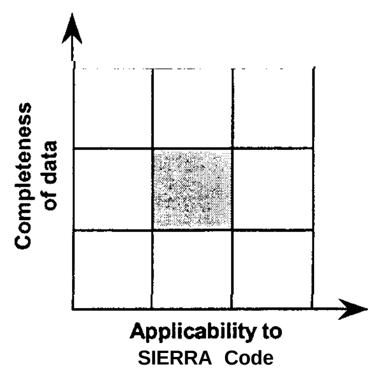
Sivathanu, Y. R., Kounalakis, M. E., and Faeth, G. M., 1990, "Soot and Continuum Radiation Statistics of Luminous Turbulent Diffusion Flames," *Proc. 23rd Symposium (International) on Combustion,* The Combustion Institute, pp. 1543-1550.

This paper describes the soot and spectral radiation properties of a highly buoyant propylene flame burning in still air. The apparatus consists of a 50 mm diameter burner injecting vertically upward within a screened enclosure. Flames with Reynolds numbers of 750 and 1370 were studied.

An optical probe was used to measure the probability density function of the soot, and the under- and over-fire absorption and under-fire intermittency. The laser absorption at 632.8 nm was measured for 10 mm optical paths within the flame. Transient spectral radiation intensities were measured using a monochromator. The experimental uncertainties are estimated to be less than 40 % for the soot volume fractions and less than 15% for the under-fire intermittency, at 95 % confidence. The experimental uncertainties of the spectral radiation intensity measurements are estimated to be less than 20 %.

Data include plots of under-fire intermittency and mean and fluctuating soot absorption and probability density functions of soot absorption in the over- and under-fire regions plotted as a function of radial location. The probability density function of spectral radiation intensities at 1000 nm and 2300 nm are also graphed. Mean and fluctuating soot statistics, intensities, and the transmittance are presented in tabular form.

This data is of limited usefulness because most data is presented as plots of probability density functions, and measurements are only taken at one axial location. Nevertheless, the experimental uncertainties are detailed and the data appears to be of good quality. This particular paper may be useful for validating the soot chemistry module of the SIERRA/FUEGO or SIERRA/SYRINX code.



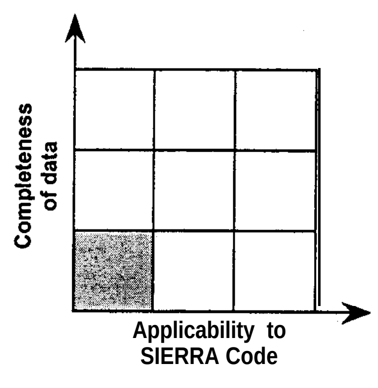
Snelling, D. R., Thomson, K., Smallwood, G. J., Weckman, E., Fraser, R., and Gülder, 6. L., 1999, "Soot Surface Temperature Measurements in a Laminar Diffusion Flame," *Proceedings, Com bustion Institute Canadian Section, Spring Technical Meetings, Edmonton AB.*

This paper presents a new technique for measuring the soot surface temperature and volume fraction by spectral measurement of radiant emission. The experimental apparatus consists of a 10.9 mm diameter fuel tube centered within a 100 mm air nozzle. The fuel-flow rate is 194 ml/min and the airflow rate is 284 l/min. The fuel, ethylene, and air are discharged and ignited within a screened enclosure to reduce the effects of ambient drafts on the flame.

Radiation emission is measured using a spectrometer. Each measurement consists of a spectrum averaged from five one-second exposures. No uncertainty estimates are provided for these measurements. The flame temperature and soot volume fraction are not measured directly, but are inferred from the measured spectral intensities. Temperature data obtained using coherent anti-Stokes Raman spectroscopy (CARS) is also presented. These measurements have error bars that suggest an uncertainty of less than 3%, but the origin of this data is not clear.

Data consists of plots of intensity and differential intensity (with respect to radial position) at eight different wavelengths, flame temperature, and soot volume fraction as a function of radial position, measured at a height of 30 mm from the fuel tube outlet.

This paper is of limited use for code validation. The spectral intensity distribution is only measured at one axial location and has no reported experimental uncertainty. Also, the velocity distribution is not provided.



Souil, J. M., Joulain, P. and Gengembre, E., 1984, "Experimental and Theoretical Study of Thermal Radiation from Turbulent Diffusion Flames to Vertical Target Surfaces," *Combustion Science and Technology,* Vol. 41, pp. 69-81

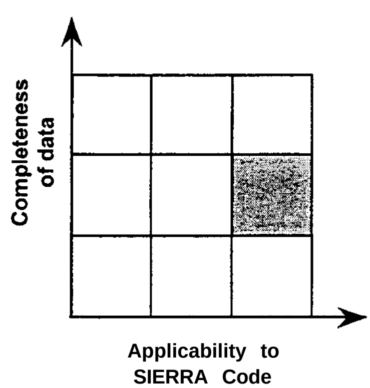
This study concentrates on radiative heat transfer to vertical target surfaces. The flames considered here are propane diffusion flames issuing from a circular burner of 0.3 m diameter. The detailed explanation of the experimental setup is referenced to Gengembre et al. (1983), which is in French. The experimental values available in that reference are used in this study as flame physical parameters for the radiative flux calculations presented.

The measurements of radiative flux are by water-cooled, wide-angle radiometers viewing the flame at a distance Ro=3 m from the burner axis, and the flux measurements are collected as a function of the height of the sensor above the base of the burner.

This study focuses on the forward radiative transfer from the flames to vertical target surfaces for the study of fire progress in a room fire situation. An array of 4 wide-angle radiometers is used with sensitive surfaces located in a vertical plane at the same height from burner. The first sensor is located perpendicular to the burner axis and the others are located 0.25 m apart from the first one and each other on a horizontal line on the same side of the burner axis. Radiative fluxes are presented for four points at different heights for 4 different sets of total fire heat outputs and distance to fire configurations. These are 15.8 kW and 0.3 m, 15.8 kW and 0.4 m, 22.9 kW and 0.3 m, 37.9 kW and 0.3 m. The temperature distributions in the flame axes at different heights are also presented for a total heat output of 15.8, 22.9 and 37.9 kW.

Two approaches are used for calculations of the heat flux to compare the results; one that uses detailed experimental information of temperature and absorption coefficient distributions and one based on isothermal and homogeneous absorption coefficient. The flame shape and the absorption coefficient distribution for the first approach is referenced to Gengembre et al (1983), while the isothermal values are specified here.

This paper overall can be very useful for Sandia's validation purposes. Although the flame is not a pool fire flame, it is a turbulent diffusion flame with a defined shape, temperature and absorption coefficient distribution. The main drawback of the paper is that it references this information to papers in French. If the referenced paper is available and translated, this paper is can be very useful to validate the SIERRA/SYRINX code that calculates the radiation transfer.



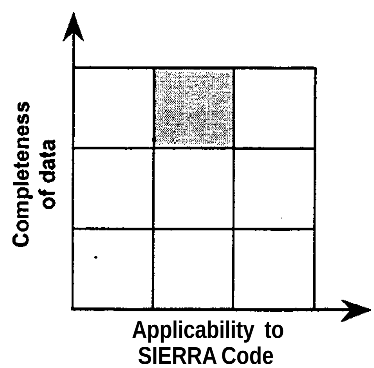
You, H-Z., and Faeth, G. M., 1982, "Buoyant Axisymmetric Turbulent Diffusion Flames in Still Air," ***Combustion and Flame,*** **Vol. 44, pp. 261-*275.***

This paper presents the structure of turbulent buoyant diffusion flames, which are then used to evaluate theoretical models. The experimental apparatus consists of a vertical burner tube, which discharged natural gas into a screened room in order to minimize the effects of ambient drafts. The natural gas was ignited at the burner exit, and was attached to the lip of the burner. Flames with heat outputs of 1.67 and 8.51 kW were studied, which corresponded to Reynolds numbers of 70 and 356 at the burner exit, respectively.

Data include plots of the axial variation of mean temperature, mean velocity, velocity fluctuations, Reynolds stress, and the mass fractions of N_2, O_2, CO_2, H_2O, CH_4, CO, and H_2, as well as radial plots of these quantities at three axial stations for both flames. The axial variation of radiant heat flux is also plotted for both flames.

Mean velocity, velocity fluctuations, and Reynolds stresses were measured with a laser Doppler anemometer. The total experimental uncertainties are not included for these methods, but gradient broadening errors (which are typically the dominant source of error) are estimated to be less than 10%. The temperature field is determined using a thermocouple array. Error bounds are presented graphically with the temperature data. Gas composition was determined with a gas chromatograph. Radiant heat flux was measured using a water-cooled, gas-purged stationary sensor. No experimental uncertainties are included with these measurements.

This paper should prove to be very useful for the purposes of the present study, since the velocity and temperature fields are well defined, and axial variation of radiant heat flux is presented. Also, the experimental apparatus is thoroughly described, which should facilitate numerical simulation. Unfortunately, the experimental uncertainty for most data is not provided.



ENCLOSURE FIRES

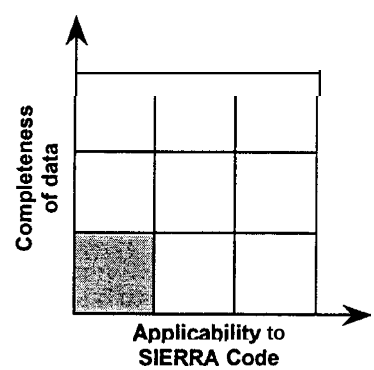
Brehob, E. G., and Kulkarni, A. K., 1998, "Experimental Measurements of Upward Flame Spread on a Vertical Wall with External Radiation," *Fire Safety Journal,* Vol. 31, pp. 181-200.

The purpose of this paper is to study the effect of incident radiation on the flame speed along a vertical surface, which occurs in enclosure fire conditions. Infrared heaters provided up to 15 kW/m^2 of incident radiation on samples of practical building materials, and the flame (or pyrolysis) height is recorded as a function of time. This data is to be used to develop and validate a numerical flame spread model.

The experimental apparatus consists of a 30 cm × 120 cm panel, mounted vertically so that the longer side is perpendicular to the ground. A propane line burner was used to ignite the lower edge of the sample. Two electric-powered infrared heater panels were angled towards the sample to simulate the radiant heat transfer to the sample that would occur if it were placed in a burning room.

Materials tested were clear solid polymethyhrethacrylate (PMMA), Douglas fir particleboard, fire retardant plywood, poplar, cotton textile, hardboard, and gray laminated cardboard. Data include graphs of the flame height as a function of time for different levels of incident radiant heat flux, sample preheat, and igniter strength. The total heat feedback was also measured at five heights along the particleboard sample face, using Gardon-type radiant flux gages. No error analysis is included.

This paper is moderately useful for validating the fire module of the SIERRA/FUEGO or SIERRA/SYRINX code. The experimental data is useful for validating flame propagation in enclosure fires. The radiation feedback data is of particular interest since it describes the effect a fire has on an object located outside of the fire, which is a scenario that is relevant to the present study. Unfortunately, no differential (velocity and temperature) measurements were made in the fire field, and no experimental uncertainty is provided. Moreover, the materials considered are common building materials, and not likely to be encountered in the present application.

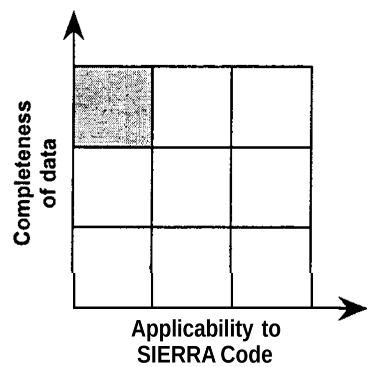


Butler, B.W. and Webb, B.W., 1993 "Measurement of Radiant Heat Flux and Local Particle and Gas Temperatures in a Pulverized Coal-Fired Utility-Scale Boiler," *Energy and Fuels,* Vol. 7, pp. 835-841.

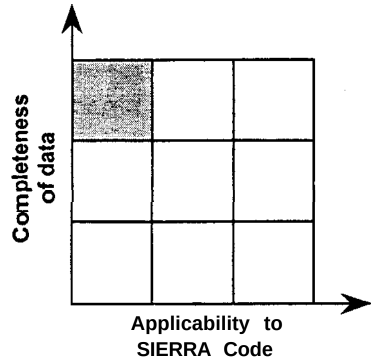
The paper presents experimental measurements of local particle and gas temperatures in an industrial scale boiler where the bulk of the energy transfer occurs by radiation, and radiation is dominated by flame emission rather than wall effects. The boiler is an 80 MW tangentially fired unit operated by New York State Electric and Gas. The analysis is carried out using two different coals. The proximate and ultimate coal analyses, furnace geometry and operating parameters are presented in detail.

Spatially resolved gas and particle temperature data are presented. These were acquired concurrently with measurements of gas species, gas velocities, particle size distribution, number density, particle velocity and char burnout data reported elsewhere. The uncertainty in measured temperatures is presented as ±40 K. The radiant heat flux on the walls is measured at different heights and axial locations. The authors present a rough overall energy balance to verify their heat flux measurements. This paper, accompanied with several related M.S. theses and Ph.D. dissertations referenced in the paper, provides very detailed information to model an industrial scale furnace.

This paper bay be useful for validationg the radiation module of the SIERRA/FUEGO or SIERRA/SYRINX code, given the comprehensive nature of the presented data. Unfortunately, it may be extremely difficult if not impossible to accurately model a coal-fired reactor with the SIERRA/FUEGO or SIERRA/SYRINX code.



Butler, B. W. and Webb, B. W., 1991, "Local Temperature and Wall Radiant Heat Flux Measurements In an Industrial Scale Coal Fired Burner," *Fuel*, Vol. 70, pp. 1457-1464.



This paper presents experimental data gathered at the New York State Electric and Gas Goudey plant, in boiler no. 13, which is an 80 MW pulverized coal combustor fired tangentially.

The data include wall radiant heat flux, measured around the periphery at six different elevations. The comprehensive data set presented includes the local gas temperature at four axial positions, boiler operating conditions, proximate, ultimate and particle size analyses of coal.

The uncertainty of the measured temperatures and the heat fluxes are presented as ±30 K and ±5%, respectively. The overall energy balance estimation that is presented roughly states the confidence to the gas temperature and radiation heat flux measurement.

This paper presents a study that is performed to provide data to verify radiation models developed for coal combustion systems. Although Sandia National Laboratories interests do not involve coal combustion in enclosures, use of this paper with several referenced theses and dissertations could be helpful to validate a radiation solver as they present a complete data set so that a radiation problem can be set in isolation from turbulence and chemical kinetics.

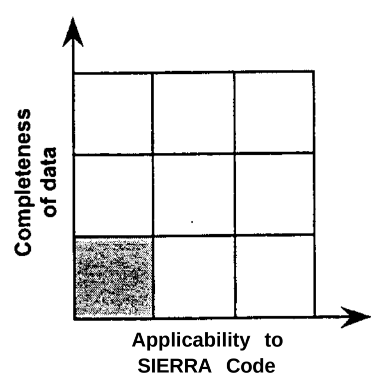
Dembsey, N. A., Pagni, P. J., and Williamson, R. B., 1995, "Compartment Fire Experiments: Comparison with Models," *Fire Safety Journal,* Vol. 25, pp. 187-227.

This paper presents experimental data from compartment fires for the purposes of evaluating the performance of two numerical models. The experimental apparatus consists of a room with dimensions 2.5 m x 3.7 m in plan, and a height of 2.0 m. The compartment had one doorway with dimensions of 0.76 m x 2.0 m, centered on one of the shorter sides. The walls and ceiling consist of ceramic fiberboard backed by gypsum, and are covered with a stainless steel sheeting coated with an industrial heat-resistant paint. A 0.61 m x 1.22 m porous propane surface burner was located at a height of 0.61 m above the floor, and at different horizontal locations for each test. Heat was supplied at a steady rate between 330 and 980 kW for the duration of each experiment. The experiment started at the moment of ignition, and ended when the rate of wall temperature change decreased below 3 K/min, at which point the system is said to be in quasi-steady state.

Temperature profiles are measured using thermocouple arrays located on the compartment walls, floor, and suspended within the enclosure. Radiation errors were corrected using five aspirated thermocouple probes, located throughout the enclosure. Radiation heat fluxes are calculated using the wall and floor temperature histories, and by assuming that the walls and ceiling are semi-infinite solids. No experimental uncertainty estimates are provided.

Data include a plot of the maximum gas temperature as a function of fire size (heat rate), and a plot of the gas temperature as a function of time. Radiation data include plots of the net incident heat flux on a wall as a function of elevation, as well as the average combined convection/radiation heat transfer coefficient and average incident heat flux as a function of fire size. Tables of the steady state gas temperatures 0.1 m below the ceiling, and the bulk centerline temperature, ceiling jet temperature, flame entrainment height, mean flame height, average floor radiant heat fluxes, and average net heat fluxes for each experiment are also included.

This paper shall be somewhat useful for this project, given the comprehensive nature of the temperature measurements. Also, the detailed description of the test compartment should facilitate computational modeling. Unfortunately, the nature of the heat flux calculations renders the accuracy of these data questionable.



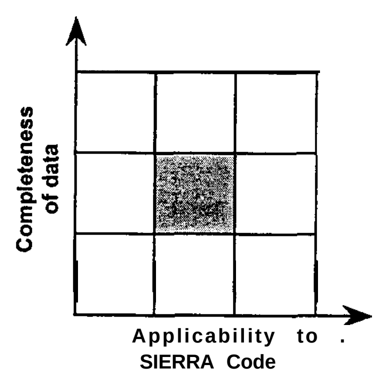
Foley, M., and Drysdale, D. D., 1995, "Heat Transfer from Flames Between Vertical Parallel Walls," *Fire Safety Journal,* Vol. 24, pp. 53-73.

The purpose of this paper is to study heat transfer from flames to vertical surfaces with an emphasis on the modeling of flame spread in confined spaces with bulk storage, particularly warehouses. The experimental apparatus consists of an instrumented vertical surface, exposed to flames from a propane line burner. The walls were two 610 mm x 813 mm x 25 mm Monolux (incombustible) boards, oriented so that the 813 mm edge was vertical. An incombustible baseboard was placed between the boards that could be removed to allow airflow vertically into the space between the walls; otherwise, air was entrained from the horizontal gap between the walls. The separation between the walls ranged from 60 mm to infinity (where only one wall was included.) A 600 mm long propane line heater was located between the two walls and rested on the base, parallel with the 610 mm side. Fuel flow rates of 5 and 9 l/min were used, corresponding to 7 and 12.7 kW respectively.

Four Gardon-type radiometers were installed at four vertical stations on one board; these could be moved between four horizontal stations at each elevation, resulting in a 16-point heat flux distribution over the wall. Although no error analysis is included for these measurements, one quarter of the experiments were duplicated and the results were found to have a repeatability of 9%.

Data include plots of heat flux as a function of wall separation and height above burner. Contour plots of heat flux taken at 16 measurement locations with open and closed base configurations are also included.

This paper should be very useful for validating the radiation module of the SIERRA/FUEGO or SIERRA/SYRINX code. The experimental data describes the radiation heat transfer between a fire and an object located outside of the fire, which is a scenario of particular interest to the present study. The experimental configuration is described in detail, and should be easy to simulate. Also, the heat-flux measurements are quite comprehensive, and are presented in a convenient manner. Unfortunately, a detailed uncertainty analysis is not provided, and velocity and temperature data are not presented.



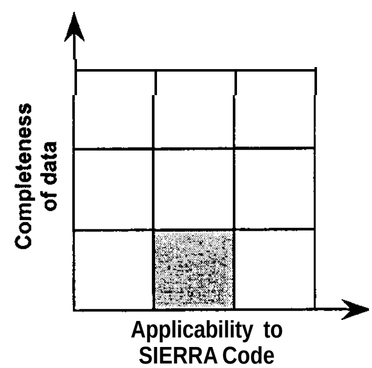
Gengembre, E., Cambray, P., Karmed, D., and Bellet, J. C., 1984, "Turbulent Diffusion Flames with Large Buoyancy Effects," *Combustion and Flame*, Vol. 41, pp. 55-67.

This paper presents the chemical composition, temperature, and velocity fields of a turbulent diffusion flame for the purposes of modeling room fires. The experimental apparatus consists of a 30 cm burner that contains about 2000 juxtaposed alumina tubes (5 cm long, 4 mm ID, 7 mm OD). The burner is oriented vertically, and propane is fed through the burner assembly and is then ignited. The burner assembly sits in the center of an uncovered 4 m x 4 m x 3.6 m enclosure, which minimizes the effects of ambient drafts on the flame. The enclosure walls have 1.2 m^2 apertures to permit combustion airflow. Flames with heat outputs of 16, 23, and 38 kW were studied.

Combustion products were measured using gas chromatography or by specific infrared analysis. No uncertainty estimates are provided for these measurements. The temperature field is determined using a thermocouple array, and an error of up to 60 K due to radiation effects is thought to occur in the hottest area of the flame. Velocity measurements are made by laser Doppler anemometry. No error analysis is provided for these measurements.

Data include plots of the mole fractions of combustion products (CO, CO_2, C_nH_m, O_2, and N_2), mean temperature, temperature fluctuations, *rms* vertical and radial velocity components plotted as a function of axial location (scaled by the flame heat output) and radial location at the burner exit plane.

This paper may be used to validate the fluid mechanics module of the SIERRA/FUEGO or SIERRA/SYRINX code, since the velocity and temperature profiles of this fire are well documented. Unfortunately, no radiation measurements are presented, and a detailed uncertainty analysis is not provided.



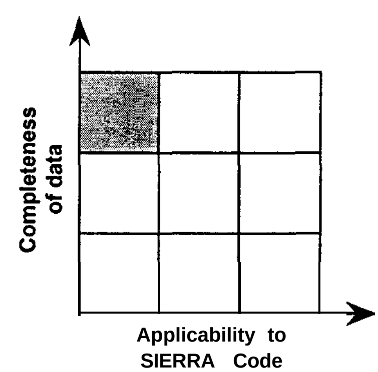
Hwang, Yuh-Long and Howell, John R., 2001, "Local Furnace Data and Modeling Comparison for a 600MWe Coal-Fired Utility Boiler? accepted, *Journal of Energy Resources Technology,* March.

This paper presents measurements inside a coal-fired 606 MWe utility boiler. Complete specification of the geometry, fuel (including proximate analysis), burner locations and angle of firing, overfire air damper settings, and excess O_2 are given. Experiments for many different combinations were performed.

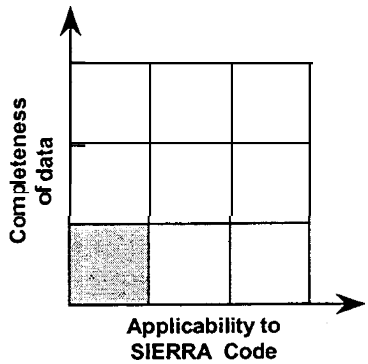
Measurements of temperature distributions within the furnace were made on four sides at insertion depths of up to 2.41 m from the wall and at various furnace elevations. These measurements are given for each combination of input parameters, along with radiative and total heat fluxes at the wall and stack NO, and excess O_2 concentrations. Temperature measurements are stated to be within ±5°C, radiative flux measurements within ±50 kW/m^2 (in ranges up to 500 kW/m^2) and total heat flux measurements within ±60 kW/m^2 (in ranges up to 600 kW/m^2). Stack NOx measurements are given as ±5 percent and stack excess O_2 as ± 4 percent.

Measurements are compared with predictions from a 3-dimensional comprehensive code developed at Brigham Young University with varying degrees of agreement. Temperature and flux predictions are in reasonable agreement, but the NO, predictions were quite poor. This is ascribed to the need for tine grid resolution to resolve the NO, chemistry as well as a poor model for NO, in the version of the code used for prediction. This paper provides the most detailed data available for verification of a code for very large coal-fired systems.

For the purposes of the present study, the geometry and the presence of complex coal chemistry and the lack of soot and ash concentration measurements probably make the work less useful than papers that describe less complex systems.



Ingason, H., 1998, "Modeling of a Two-Dimensional Rack Storage Fire," ***Fire Safety Journal,*** **Vol. 30, pp. 47-69.**



This paper presents a two-dimensional theoretical model for simulating the fire in a rack-storage facility (e.g. a warehouse), which is validated by a comparison to experimental data. The experimental apparatus consists of rectangular Navilite boxes (0.59 m × 0.235 m x 0.22 m) held up by two narrow steel columns. The rack storage is two boxes wide and four boxes high. A 590 mm ling propane burner was placed on the floor centered between the two racks, oriented parallel to the 0.59 m edge of the boxes.

Temperature and velocity were measured using an array of K-type thermocouples and bi-directional probes, located along the centerline of the vertical flue between the two racks.

Data include a plot of air mass flow rates at different tiers, flame heights, centerline temperature, and velocity as a function of burner heat output. No experimental uncertainty is reported for this data.

The applicability of this paper to the present project is very limited. The experiment is unlike any accident scenario of interest. Also, no radiation data is included, and temperature and velocity measurements are taken at very few stations. Furthermore, no experimental uncertainty is included with the data.

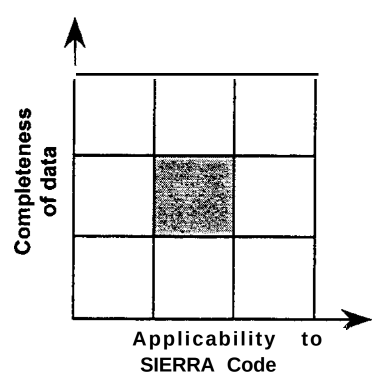
Ingason, H. and de Ris, J., 1998, "Flame Heat Transfer in Storage Geometries," *Fire Safety Journal'*, Vol. 31, no. 1, pp. 30-60.

This paper presents the heat flux distributions to the four square steel towers, of size 0.3x0.3x1.8 m, exposed to turbulent buoyant flames. Three different fuels, carbon monoxide, propane, and propylene are used, leading to flames with different soot content. The fuel is supplied from a circular gas burner at the bottom. The geometry of the system is presented thoroughly for the four steel towers that represent a typical storage arrangement in a warehouse. The entire apparatus is enclosed by four walls made of gypsum board, to minimize the effects of ambient drafts.

The temperatures and heat fluxes are measured by the use of thermocouples at 52 different locations and the locations of the thermocouples are presented in the paper. Total heat flux is measured by welding a thermocouple between a sheet of stainless steel and an insulating layer. The total heat flux incident on the steel is calculated based on the rate of temperature rise measured by the thermocouple. Total heat flux was also measured at one location using a thermopile detector. Intensity measurements were made by radiometers that were located at three heights and aimed at the fire axis.

The temperature of gas before ignition, ambient temperature, chemical and convective heat release rates, total mass-entrainment rate of air, the average velocity at the floor and the Reynolds number are provided for several different configurations. The total heat flux to the surfaces of the square towers are presented with the temperatures of the surfaces and gas. The flame radiance and centerline gas velocity are also presented. The paper also presents correlations developed based on the results for the range of sootiness between 0 and 5.6 where the experiments are carried out. The maximum errors for the measured and calculated values are estimated to be below 5 %.

Although this paper describes the gas temperature within the flame, the emphasis is on the interaction of a fire with its surroundings rather than the properties of the fire itself. Accordingly, this paper would be most useful for validating the SIERRA/FUEGO or SIERRA/SYRINX code when it is used to predict the heat transfer to an object that is located outside the pool fire.



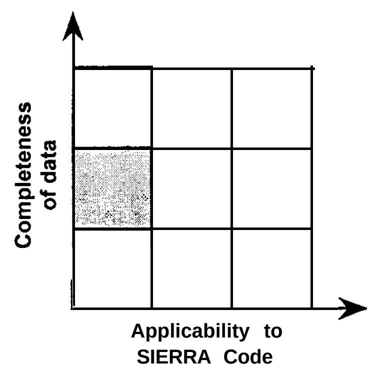
Pavlović, P., Jović, L., Jovanović, L., and Afgan, N. H., 1974, "Steady and Unsteady Heat Flux Measurement on the Screen Tube of a Power Boiler Furnace," from *Heat Transfer in Flames,* Afgan, N. H. and Beer J. M. Eds., Scripts Book Co., Washington, U.S.A..

The primary purpose of this paper is to describe the development of a radiant heat flux meter, which is then used to measure the heat flux incident on boiler screen tubes in a pulverized coal furnace from a 200 MW thermal power station, although an unspecified liquid fuel was used in this experiment. The heating value of the fuel is provided, but the fuel composition is not included.

The radiant flux is calculated based on the thermal resistance between the top surface of the flux meter, which is exposed to incident radiation, and the bottom surface, which is welded onto the screen tube of the boiler. By comparing the temperatures of the two surfaces (measured using thermocouples), the incident radiant heat flux is calculated.

The experimental data of interest consists of total radiant heat flux and temperature measurements made at eighteen different stations on the furnace wall (nine stations at three levels, on two adjacent surfaces). Contour plots of the radiant heat flux, relative to the maximum heat flux, and the temperature distribution over the furnace wall are presented for two different steady-state operating conditions. An error analysis for this experiment is not included; other experiments, however, demonstrate that the static performance of the flux meter is accurate to within 5%.

This paper will likely prove not be useful for validating the SIERRA/FUEGO or SIERRA/SYRINX code. None of the data is tabulated, and absolute magnitudes of the heat flux measurements are not presented. Moreover, since the exact composition of the fuel is not specified, numerical simulation of this experiment is impossible.



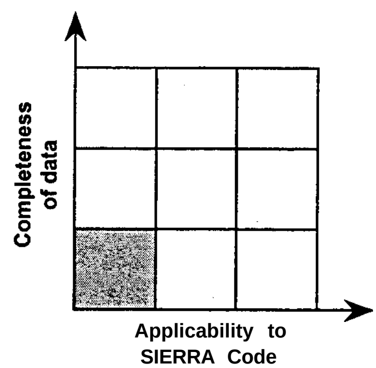
Spearpoint, M. J., and Dillon, S. E., 1999, "Flame Spread Model Progress: Enhancements and User Interface," ***National Institute of Standards and Technology Technical Report*** **NIST** ***GCR 99-782.***

The purpose of this work is to enhance the Quintere Flame Spread Model, QFSM, which computes the wind-aided and opposed flow flame spread front as well as the associated burn-out fronts for a compartment lined with various materials. These modifications are based on the results of recent published works, which are repeated in the report. In particular, the height of the ignition source flame, its extension along the horizontal ceiling, and the incident heat flux to a target material are addressed. The performance of the code is assessed by comparing its predictions to experimental results.

The experimental apparatus is an IS0 9705 room/comer test, which consists of a 2.4 m x 3.6 m x 2.4 m rectangular enclosure with a gas burner in one of the bottom comers. The gas burner has a 0.17 m square area, and burns propane. The data include the flame height and the flame extension along the ceiling of the enclosure (which occurs when the flame tip reaches the enclosure ceiling) plotted as a function of the thermal output of the burner, and the heat flux emitted from the burner flame as a function of the flame height.

The data also includes the time required for the fire to reach flashover, i.e. when the thermal output exceeds 1 MW. These experiments were done for a wide variety of wall materials, and the experimental results generally compare very poorly to the numerical simulations. The time rate of energy release within the enclosure is also documented for each experiment.

Although this report contains plenty of data, the purpose of the test facility is to evaluate residential and industrial fire scenarios, so the experimental conditions do not correspond to the present application. Also, most of the data is macroscopic in nature; there is no description of the flame structure, temperature or velocity fields, or the radiant heat-flux distribution. This greatly limits the usefulness of the data for the purposes of code validation.

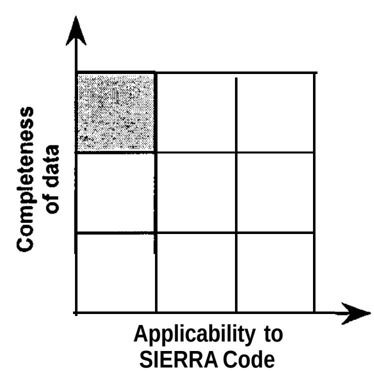


Tree, D.R., Black, D.L., Rigby, J.R., McQuay, M.Q. and Webb, B.W., 1998, "Experimental Measurements in the BYU Controlled Profile Reactor," *Progress in Energy and Combustion Science,* Vol. 24, pp. 355-383

This paper presents a summary of the experiments and some results that have been carried out in the small scale Brigham Young University controlled profile reactor. These results have been used for model validation, investigation of new concepts in combustion, and testing and development of new measurement techniques.

The results presented in the paper include experiments carried out with natural gas combustion in a swirling flow and pulverized coal combustion. Detailed information about the measurement techniques and predictions on measurement sensitivities is also presented. Although extensive data are presented of distributions of flow, temperature and the concentration of species and particles, the total and radiative heat fluxes on the walls of combustion chambers are presented only for pulverized coal combustion cases. (It is mentioned that these values were also measured for the natural gas combustion cases.) Extensive information is referenced to several Ph.D. dissertations. The heat flux distributions are presented in section three of the paper. The uncertainty of the measurements of temperatures is estimated as 2.5 percent in the flame zone is presented as 10 percent for the heat flux on the walls. Monochromatic transmission rate at a wavelength of 632 nm is also measured with a mean uncertainty of 3 percent. No results are presented for the radiative properties of the medium, surface or particles over the whole spectrum but these properties could be obtained elsewhere.

The paper provides a detailed description of the furnace geometry, which should facilitate numerical modeling. Also, the comprehensive nature of the data (radiation, temperature, and velocity measured at many locations) and the detailed uncertainty analysis makes this paper a potentially valuable source of data. Unfortunately, most of the data was obtained during operation with pulverized coal, which may be difficult if not impossible to model with SIERRA/FUEGO or SIERRA/SYRINX.



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APPENDIX A: DATA CONTENT OF REFERENCES

Table 1: Summary of Lab-Scale Pool Fires References

Reference	Radiation	Velocity Distribution	Temperature Distribution	Soot Properties	Combustion Product Composition	Turbulence Statistics
Bouhafid et al., 1988			1	2	1	
Burgess and Hertzberg, 1974	3		3			
Choi et al., 1994	2		2	2	2	
Crauford et al., 1985		1	1			
Fisher et al., 1987	1	1	1		1	
Hamins et al., 1994	1					
Hamins et al., 1991	2					
Hogben et al., 1999	3		3			
Inamura et al., 1992	2					
Joulain, 1996	2	2	2			
Klassen et al., 1992	1		1	1		
Koseki, 1994	2		1			
Koseki et al., 2000	2		1			
Koseki and Yumoto, 1988b	1	2	2			
Markstein, 1981	1					3
Modak and Croce, 1977	3					
Orloff, 1981	2		2			
Shinotake et al., 1985	1			2		
Sivathanu and Gore, 1992	3		1	1		2
Weckman and McEwen, 1991		1	1			
Weckman and Strong, 1996		1	1			1
Zhang et al., 1993	2		1			
Zhang et al., 1991			1	2	1	

Rankings are from 1 (complete data) to 3 (sparse data).

Table 2: Summary of Large-Scale Pool Fire References

Reference	Radiation	Velocity Distribution	Temperature Distribution	Soot Properties	Combustion Products Composition	Turbulence Statistics
Brosmer and Tien, 1987	1			2		
FABIG, 1997						
Gregory et al., 1989	1		1			
Gritzo et al., 1998			1			
Koseki, 1999	3		2	2		
Koseki et al., 2000	3	1	3	2		
Koseki and Yumoto, 1988a	1	2	1		2	
Kramer et al., 2001	1		1			
Nakos et al., 1991			1			
Russell and Canfield, 1973	1		1			

Rankings are from 1 (complete data) to 3 (sparse data).

Table 3: Summary of Momentum-Driven Fire References

Reference	Radiation	Velocity Distribution	Temperature Distribution	Soot Properties	Combustion Products Composition	Turbulence Statistics
Bennet et al., 2000			2		2	
Delichatsios and Orloff, 1988	2					
Faeth et al., 1989	2	2	2	3	3	
Faeth et al., 1988	2			1	2	2
Gore and Faeth, 1986	1			3	2	2
Gore et al., 1986	1		2		2	
Gore et al., 1987	1	2	2		2	2
Gülder, 1992				2		
Gülder et al., 2000				1		
Jeng and Faeth, 1984a	1					
Jeng and Faeth, 1984b			1		1	1
Jeng et al., 1984	2		2		2	
Jeng et al., 1982	3	1	1			1
Kennedy et al., 1986		1	1	1	1	
Liu et al., 2001			3			
Markstein, 1977	2					
Mbiock et al., 2001		2	2		2	
Sandia-Livermore Website						
Sivathanu and Gore, 1993	2				2	
Sivathanu et al., 1990	3			2		
Snelling et al., 1999	3		2	2		
Souil et al., 1984	2		1		2	
You et al., 1982	2	1	1		1	1

Rankings are from 1 (complete data) to 3 (sparse data).

Table 4: Summary of Enclosure Fire References

Reference	Radiation	Velocity Distribution	Temperature Distribution	Soot Properties	Combustion Products Composition	Turbulence Statistics
Brehob et al., 1998	1					
Butler and Webb, 1993	1	1	1		1	
Butler and Webb, 1991	1		2			
Dembsey et al., 1995	1		2			
Foley and Drysdale, 1995	1					
Gengembre et al., 1984		1	1		1	1
Hwang and Howell, 2001	1		1		2	
Ingason, 1998		3	3			
Ingason and de Ris, 1998	1	2	1			
Pavlovic et al., 1974	2		1			
Spearpoint and Dillon, 1999	2					
Tree et al., 1998	1	1	1	1	1	

Rankings are from 1 (complete data) to 3 (sparse data).

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